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November 1974

THE PROCEEDINGS OF THE SKYLAB LIFE SCIENCES SYMPOSIUM

AUGUST 27 - 29, 1974
LYNDON B. JOHNSON SPACE CENTER

VOLUME I

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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16. Abstract

This document contains the proceedings of the Skylab Life Sciences Symposium held at the Lyndon B. Johnson Space Center 27-29 August 1974. The three manned Skylab missions resulted in biomedical experiment data in the areas of neurophysiology, musculoskeletal physiology, biochemistry, hematology, cytology, cardiovascular and respiratory metabolic functions: as well as detailed test objectives involving crew health and environment procedures. Major emphasis was placed on results from the last mission, Skylab 4, which covered 84 days of in-flight data collection. Many new norms were defined for "normal" man living and operating in a unique environment. While man is quite adaptable to this unique environment, many of the changes observed in Skylab require additional research for future flights lasting very long periods of time such as a Mars mission requiring 18 months.

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INTRODUCTION

The bound copy of *The Proceedings* appears in two volumes. The papers received for reproduction have been grouped into three major sections: Introduction, Detailed Test Objectives and Medical Experiments, and Symposium Summary. The Detailed Test Objectives and Medical Experiments have been further divided into five subsections: Introduction, Neurophysiology, and Musculoskeletal Function comprise Volume I; Body Fluids/Hematology, Cardiovascular/Metabolic Function and Symposium Summary comprise Volume II. The papers appear according to the order of presentation at the Symposium, but there are minor variances between contents of *The Proceedings* and the presentation due to the constraint of time imposed by the length of the program. Two papers included in *The Proceedings* were "read by title only" at the Symposium because of late submittal, *i.e.*, Red Blood Metabolism and Determination of Cardiac Size from Chest Roentgenograms Following Skylab Missions. Another paper, Immunity (M112), also "read by title only" has not, as yet, been submitted.

A separate Table of Contents and Index of Authors/Panelists is included in each volume for ease of reference. Every attempt had been made to minimize the size of *The Proceedings* and to facilitate reference of an author or his/her paper.

Sylvia A. Rose

November, 1974.

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FOREWORD

Good morning ladies and gentlemen; I would like to welcome you to the Skylab Life Sciences Symposium. For the next three days we will present the results of an exhaustive series of medical studies conducted on missions of 28, 54 and 84 days.

Before we move into the business at hand, I might take a few minutes to set the stage for our later presentations.

In the history of man's first small steps toward ultimate flight to the planets and to distant stars, some notable milestones have been achieved. As we have moved along, step by step, the impact of our accomplishements has swung from one discipline to another. The successful launch of Alan Shepard into suborbital flight in 1961 was a tremendous boost for rocket specialists. It was, in fact, possible for U.S. rockets to launch a manned spacecraft. In the mid-1960s, the Gemini rendezvous and docking successes were particularly rewarding for guidance engineers and those concerned with space mechanics. In Apollo, the materials brought back from the lunar surface had a special impact for the physical scientist. Now we come to Skylab, and the focus of attention moves to the life scientist. Skylab was, in many respects, our flight. The reams of data returned from these missions provide our first real picture of how man lives in space. We already knew, of course, that man could *exist* in space and that he could *work* in space. Well before Skylab we solved or understood the principal problems of life support, of food service, and of waste management. But it was not until Skylab that we learned that man could truly *live* in space.

I am happy to report that no major medical finding will be presented which might curtail man's dreams of more extensive space exploration, rather we have found that man can adapt to the new and wonderous environment of space.

Many individuals have made a personal commitment to the success of Skylab and previous manned spaceflights, unfortunately all of these people will not be able to take part in these presentations. All of

us with NASA appreciate the outstanding contributions of these individuals from other nations, the aerospace industry, universites, medical schools and other departments of government in making the space program one which we can all look to with pride. It is truely our honor to open this symposium and to have been a part of the Skylab medical team.

Director of Life Sciences

Deputy Director of Life Sciences

Lyndon B. Johnson Space Center

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SYMPOSIUM INTRODUCTION

SKYLAB MEDICAL PROGRAM OVERVIEW

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INTRODUCTION

History is filled with examples of man's desire to explore new frontiers. Having sensed the thrill of discovery, man has pressed on to scale new heights, not weighing the cost or personal risk, but mindful only of his destiny to conquer the unknown. He crossed the seas in open boats and the wastes of the arctics on dog sleds. He perished, but rose again until there were no longer any new seas to cross or mountains to climb, or arctic poles to visit. He had explored his Earth.

Exploration has always been a risky undertaking and preservation of life and health is essential to the successful conquest of the unknown. Few explorers, however, have conducted studies on themselves in order to document their responses to new environments. A notable exception was the work conducted during the 1935 International High Altitude Expedition to the Chilean Andes, when the members of that team conducted studies on themselves to record for medical science the effects of exposure to the hypoxic environment of high altitudes. Every student of space medicine has used some of the data obtained on that expedition.

Man's opportunity to explore is largely dependent upon the advancement of technologies in transportation and life support.

Some provocative fiction had been written about rocket trips to the Moon, but the technology was not available to make the dreams come true. With the development of chemical propellants and the application of some fundamental laws of physics high velocity rocket propulsion became a reality; it was all man needed to kindle his imagination to reach beyond his Earth to start the exploration of his universe.

Utilizing the Sature V launch system, man has successfully completed the lunar exploration program epoch. Through the use of this same propulsion system, the United States has launched its first long-term space station and has now made giant advancements in acquiring knowledge concerning the physiological effects of increasingly extended periods of exposure to the space flight environment and in determing how well man can function while performing tasks in space.

Space medical studies using experimental animals were initiated prior to 1959. The Project Mercury Program afforded the first opportunity for the United States to perform limited medical studies and observations on men in space. After Project Mercury (1-4), many basic concerns about the frailties of the human space explorer were dispelled. It was shown that man could operate effectively during the acceleration periods of launch and entry, and he could adapt to the weightless environment and perform useful tasks. Medical measurements made during the early flights showed that normal body functions were not adversely altered. A few changes occurred which were moderate but reversible. Postural hypotension, for example, was observed when the astronauts returned to the Earth's gravity field.

The Gemini Program (5) provided the opportunity to conduct the first series of medical studies during weightless flights. One of the objectives of the Gemini flights was to evaluate the performance of men in the space environment for 14 days to insure that they could operate effectively on a trip to and from the Moon. The results of the Gemini flights further demonstrated that man could perform useful tasks, could adapt to the weightless environment, and could enter Earth's atmosphere and readapt to Earth's gravity.

The Apollo Program originally included a series of medical studies to be performed during the early orbital missions. After the tragic Apollo 204 accident, the decision was made to delete the medical studies and to dedicate all resources to the complex lunar landing program. Consequently, medical studies were conducted with the Apollo crewmen primarily before and after each flight.

Skylab, originally called the Apollo Applications Program was a natural and necessary follow-on to the Gemini and Apollo programs. The tested and proven spacecraft and launch vehicles from the Apollo missions were used in the design and flights of the Skylab program. The development of medical experiments was initiated in the mid 1960's and a decision was made to design the experimental program along classical lines of medical and physiological research; namely, to group related studies together according to their contribution to the understanding of the functioning of a major body system. Of course the results from the previous flights influenced the planning and placement of emphasis for the new program. Experiments were developed to study the cardiovascular, musculoskeletal, hematologic, vestibular, metabolic, and endocrine systems in the body. It could be noted that, with few exceptions, the basic experiment protocols as originally developed remained unchanged throughout the Skylab program.

This paper is intended to provide an introduction and overview of the Skylab medical program. The papers that follow will present the significant results of the three Skylab missions.

OPERATIONAL EQUIPMENT

Several major medical subsystems were provided in the Skylab orbital workshop to sustain the crew and to protect their health.

Food System

The Skylab food system (fig. 1) was developed to provide a balanced and palatable diet which also met the necessary requirements for calories, electrolytes, and other constituents for the metabolic balance experiment. Seventy foods were available from which the crew could select their in-flight diets. Food types included frozen, thermostabilized, and freeze-dried foods. Menus were planned for 6-day turnaround cycles. Each crewman was required to consume his individually planned diet for 21 days prior to flight, throughout the flight, and for 18 days postflight. Approximately one ton of food was stowed in the orbital workshop at launch to provide approximately 400 man days of food. The ambient food was packaged and stowed in six-day supply increments and these were moved by the crewmen to the galley area for intermediate stowage, preparation, and eating. The galley area contained a freezer, a food chiller, and a pedestal which provided hot and cold water outlets, attachment points for three food trays, and body restraints to permit each crewman to sit and eat. Each food tray contained seven recessed openings to hold cans or other containers, three of which had heaters for warming the food. The food cans were constructed with membranes or other designed devices to restrain the food within the container when in zero gravity and to permit the crew to eat with conventional tableware. Drinks in a powdered form were packaged into individual bellows-like containers constructed with a drinking valve. Water when needed, was added from the hot or cold water outlets located on the pedestal. The crewmen drank from the container by collapsing the bellows.

The variety of foods provided and the general design of the food system were acceptable to the Skylab crewmen. At the suggestion of the returned Skylab 2 crew, more and varied spices were included in the later missions to improve the taste of the food.

The extension of the Skylab 4 mission for an additional 28 days required that 250 pounds of additional Skylab food would have to be launched in the Command Module. This food weight and the resulting stowage volume were excessive, therefore, a high density, high-caloric type food bar was stowed in the Command Module to provide the caloric requirements for the mission extension. The crewmen's in-flight menus were modified to include apporoximately 800-1000 calories of the food bars every third day. For Skylab 4, in addition to the 50 pounds of high-caloric type food bars, approximately 100 pounds of Skylab-type food and drinks were launched in the Command Module.

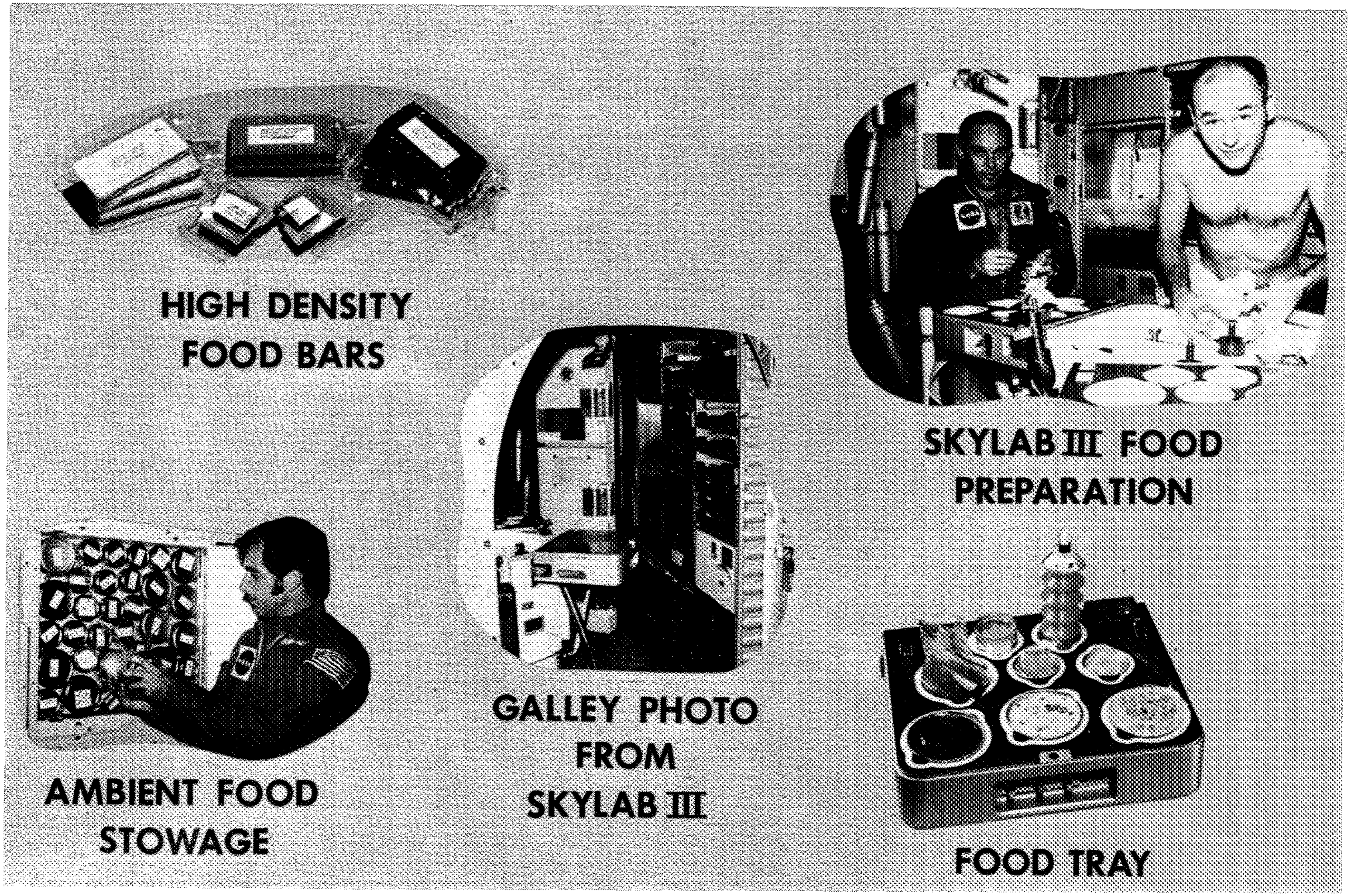

Figure 1. Skylab Food System .

Waste Management System

The Skylab Waste Management System included equipment for the collection, measurement, and processing of all urine and feces and for the management of trash such as equipment wrappers, food residues, *et cetera* (fig. 2).

Waste Management

Equipment used by the crew for the collection of urine and feces, and in addition, equipment used for personal hygiene were stowed and used in the waste management compartment. Feces were individually collected into a bag attached under a form-fitted commode seat. The bag was permeable to air and impermeable to liquids. An electric blower, actuated by the crewman during use, provided a positive airflow around the anal area to carry the feces into the collection bag. After each defecation, the crewman weighed the bagged stool on a mass measuring device, and then labeled and placed it into a vacuum drying processor. After 16 to 20 hours of drying, the bag of fecal residue was removed from the processor and stowed for return to Earth for postmission analysis.

Each crewman's urine was collected in an individual 24-hour pooling bag. A centrifugal fluid/gas separator was actuated at the start of urination to create a positive airflow to carry the urine into the equipment where urine was separated from the gas and was then collected into the pooling bag. A measured quantity of lithium chloride, added to each pooling bag prior to flight, permitted urine volumes to be calculated after analysis postflight. In addition, the crew used a gage to measure the filled pooling-bag thickness to give a real time estimate of daily urine output. Once every 24 hours each crewman collected a 120 milliliters urine aliquot from his pooled urine bag and placed this sample in a freezer for return and postflight analysis. The used pooling bag was discarded and a new bag installed for each day.

Trash accumulated from food wrappers, used equipment bags, used towels, *et cetera*, were discarded through an airlock into a large volume tank in the orbital workshop dome.

The Waste Management System and trash airlock operated satisfactorily throughout the Skylab missions and the crews reported complete satisfaction with the design of this equipment.

Personal Hygiene

Provisions were included in the orbital workshop for daily personal hygiene. Wet wipes, towels, toothbrushes, razor, deodorant, *et cetera*,

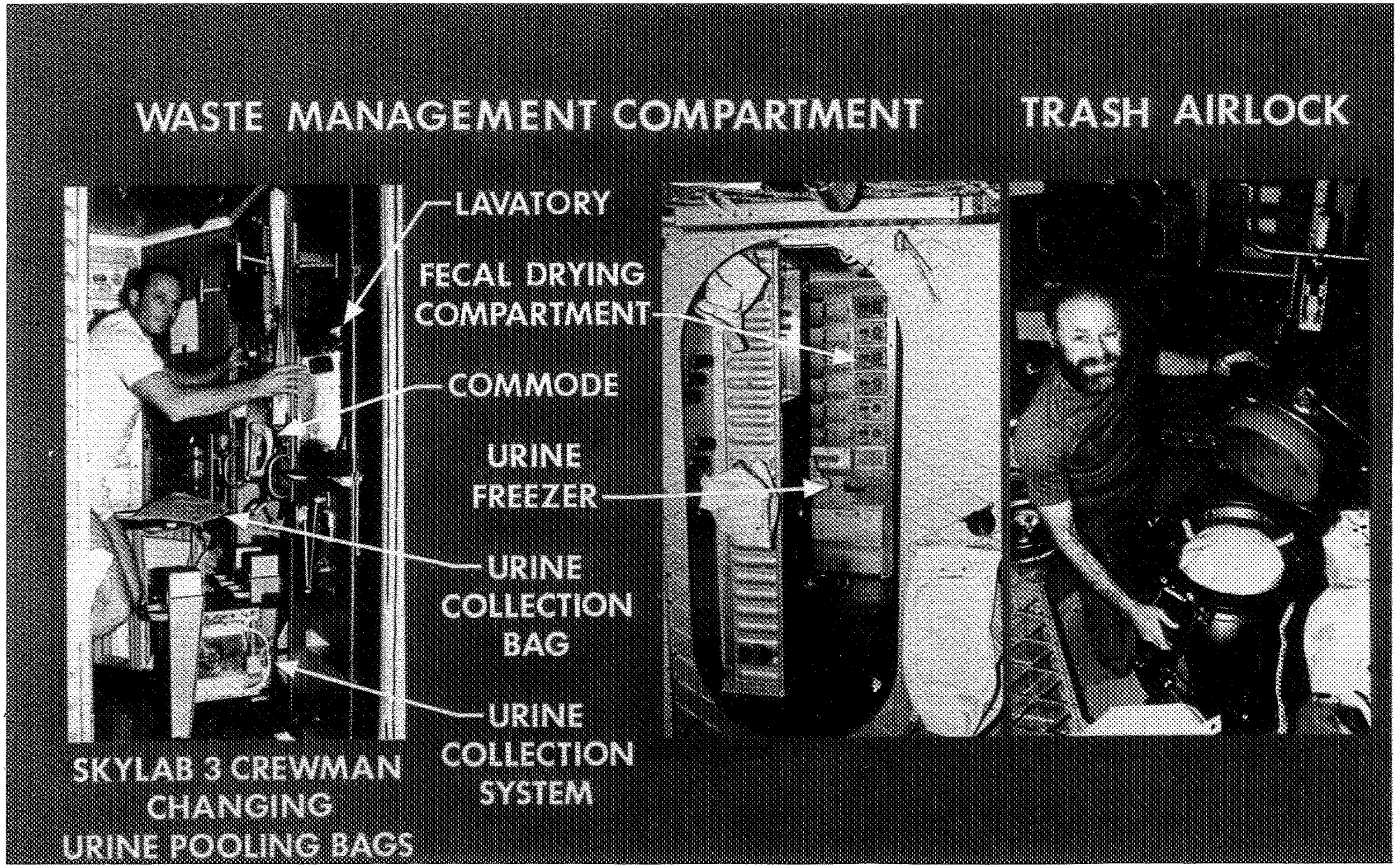

Figure 2. Skylab Waste Management Systems.

were provided to maintain body cleanliness. In addition a shower contained in a collapsible cylindrical cloth bag (fig. 3) was provided to permit full body bathing. Warm water and a liquid soap were available in limited quantity for one shower per week for each man. The Skylab crewmen reported satisfaction with the shower and other personal hygiene equipment; however, the crewmen did indicate that an excessive amount of time was required to vacuum the collected water and dry out the shower after use. Microbiological studies conducted on the Skylab crewmen indicated that the personal hygiene techniques used were completely adequate.

Inflight Medical Support System

The Inflight Medical Support System was designed to provide for the conduct of selected in-flight medical evaluation experiments and, as required, first level medical diagnosis and treatment for an ill or injured crewman (fig. 4). The equipment was stowed in the wardroom and included: diagnostic, minor surgery, dental, catheterization, and bandage kits. Sixty-two medications for the three missions were stowed in modules to insure an adequate and fresh supply. Prior to flight, drug-sensitivity testing was conducted on mission designated Skylab crewmen. In addition, microbiological equipment and slide-staining capabilities were provided. Petri dishes, an incubator, microscope, and slide stainer were available for use by the crew. The microbiological equipment was used to collect airborne and surface microbial samples in flight. As part of his mission preparation, each Skylab crewman underwent 80 hours of paramedical training in the use of the Inflight Medical Support System for diagnosis and in treatment of injury or illness.

Cardiovascular Counterpressure Garment

Cardiovascular counterpressure garments (fig. 5) were launched in the orbital workshop for all three missions. These garments were designed to provide mechanical counterpressure to the lower extremities to reduce the postural hypotension effects following landing and operations under one-gravity conditions. The garment has a built-in capstan in the length of each leg. Inflation of the capstan by a pressure bulb provided a pressure gradient of 85 to 90 millimeters of mercury (mm Hg) at the ankles to 10 mm Hg at the waist. A garment was donned by each crewman prior to entry and it was inflated sometimes during descent and always following landing. Subsequent papers will discuss the physiological protection afforded by these garments.

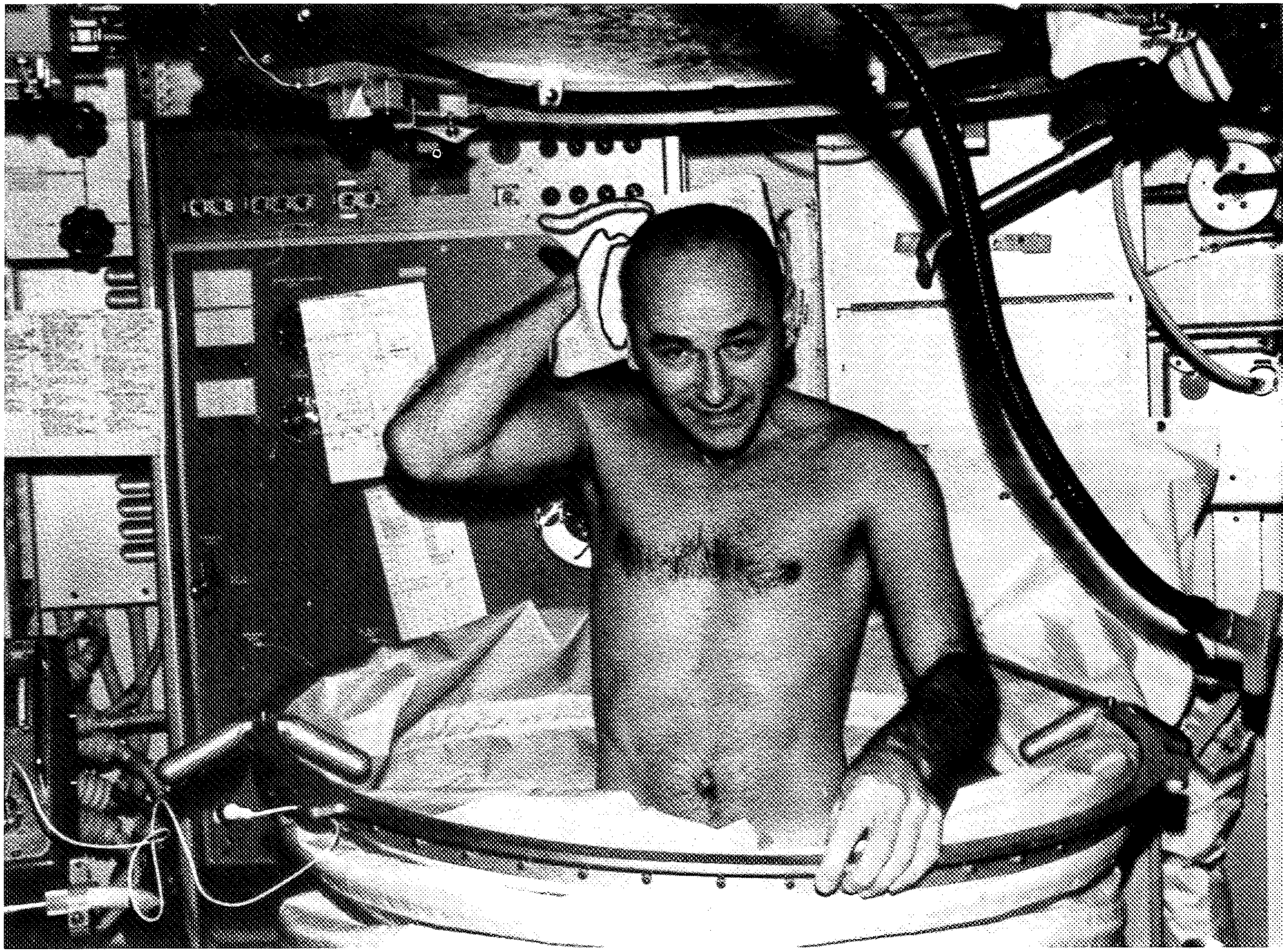

Figure 3. Skylab shower.

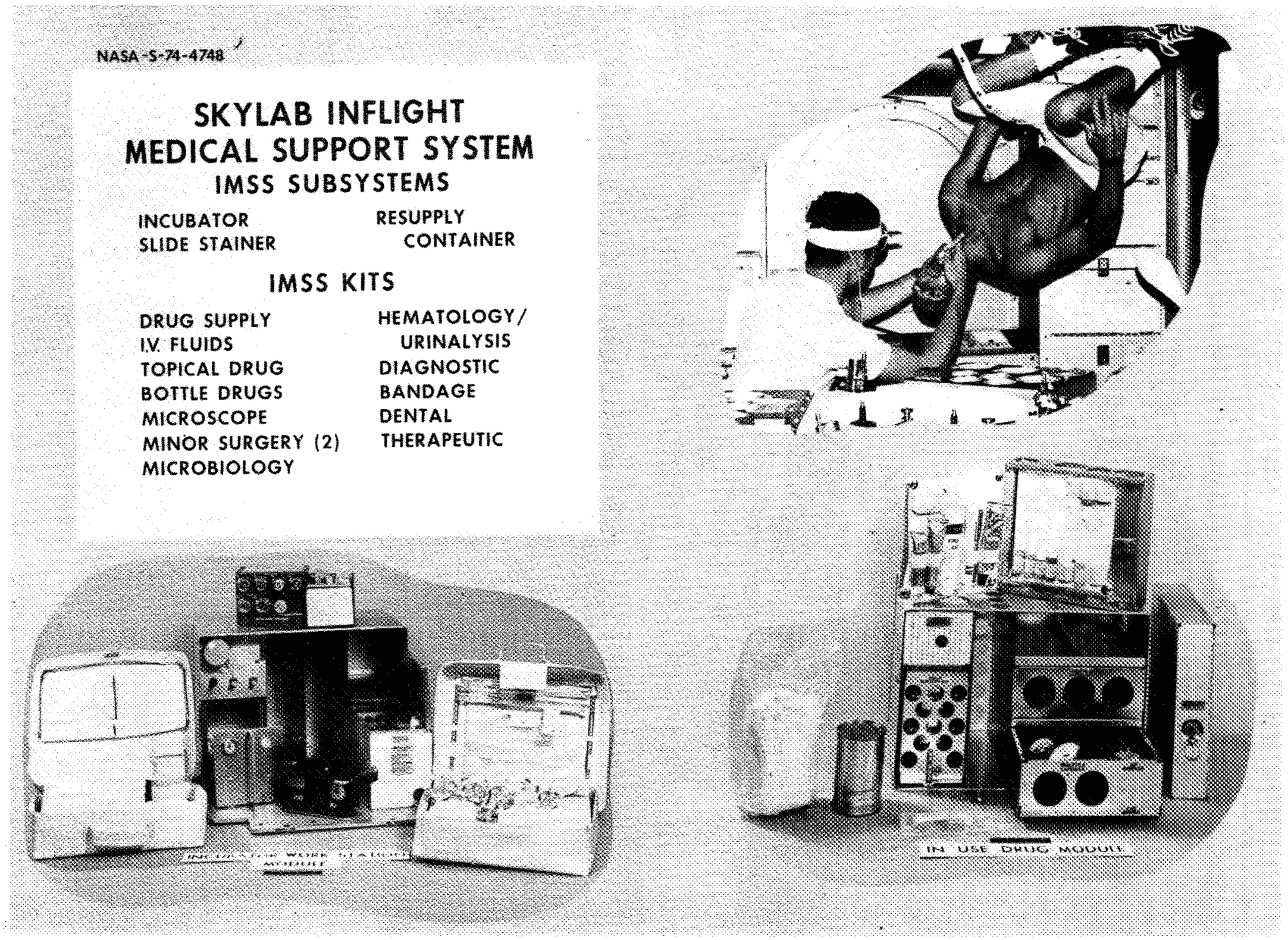

Figure 4. Skylab Inflight Medical Support System.

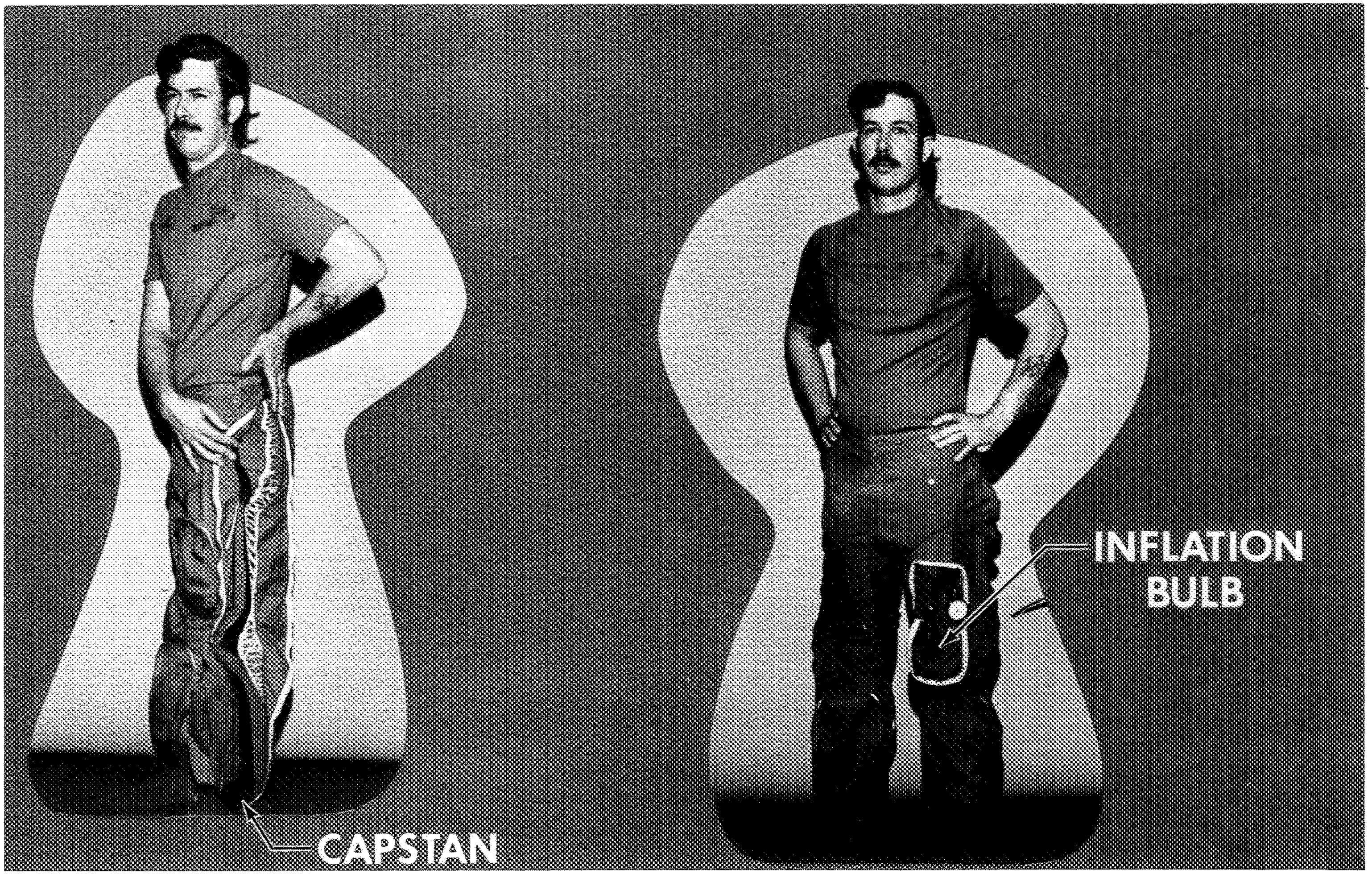

Figure 5. Skylab cardiovascular counterpressure garment.

LIFE SCIENCES EXPERIMENTS

The Skylab medical experiments listed in Table I were designed to provide an indepth study of individual body systems and at the same time provide an overlap to give comprehensive understanding of man's reaction to long-term weightless flight. Added special in-flight tests are shown in Table II to indicate other type studies which were completed in the three missions. The inclusion of major in-flight medical experiments provided the capability to study physiological responses during exposure to weightless flight as opposed to the before and after studies as carried out in the Apollo and Gemini programs. Results of these studies are the subject of this Symposium.

TABLE I. SKYLAB MEDICAL EXPERIMENTS

- ° M071 - Mineral balance
- ° M073 - Bioassay of body fluids
- ° M074 - Specimen mass measurement
- ° M078 - Bone mineral measurement
- ° M092 - Lower body negative pressure
- ° M093 - Vectorcardiogram
- ° M110 - Hematology/immunology
- ° M131 - Human vestibular function
- ° M133 - Sleep monitoring
- ° M151 - Time and motion study
- ° M171 - Metabolic activity
- ° M172 - Body mass measurement

TABLE II. IN-FLIGHT SPECIAL TESTS (ADDED)

	Skylab Mission		
	2	3	4
Blood flow		X	X
Facial photograph		X	X
Venous compliance		X	X
Anthropometric measurements			X
Treadmill exerciser			X
Center of mass			X
IR anatomical photograph			X
Taste and aroma evaluation			X
Atmospheric volatile concentration			X
Light flash observations			X
Hemoglobin		X	X
Urine specific gravity		X	X
Urine mass measurement		X	
Stereophotogrammetry			X

The Skylab medical experiments equipment were located on the crew living level of the two storied orbital workshop. The equipment occupied about one-third of the floor area of this level. Figure 6 is a photograph taken during the Skylab 3 mission; it shows this medical experiment area. On the right is the collapsed shower previously described. The two consoles against the workshop wall contain the medical experiment electronic equipment. This figure also shows photographs of two of the major medical experiments.

The M171 ergometer and metabolic analyzer shown at the upper left of figure 7 are being used by the Skylab 2 Pilot. The metabolic analyzer contains a mass spectrometer for measuring oxygen, carbon dioxide, nitrogen, and water vapor. In addition, spirometers were provided to measure respiratory volumes. The bicycle ergometer was used to provide a quantitative stress level, for investigating physiological response and it was also used as the prime off-duty crew exercise device. Blood pressure, vectorcardiograms and body temperature measurements were also taken as a part of the M171 Metabolic Activity experiment. The M092 Lower Body Negative Pressure Device is shown on the upper right of figure 7 as it was used in Skylab 2; this experiment was monitored at all times by a second crewman. The leg volume measuring bands used with the Lower Body Negative Pressure Device also are shown. The electronic center for these experiments, labeled on figure 7 as Experiment Support System, contains the displays and experiment controls.

In the lower left hand corner of figure 8, the Skylab 2 Scientist Pilot is shown wearing the M133 electroencephalographic sleep cap. One crewman, *i.e.*, the Scientist Pilot, performed this experiment in each mission. The Body Mass Measuring Device and Specimen Mass Measuring Devices were evaluated as experiments to establish the method and accuracy of determining mass in the weightless environment. In addition, these devices were used to provide daily body weights and the mass of food residues and fecal specimens. The M131 rotating litter chair was used to study vestibular functions and susceptibility to motion sickness.

Equipment also was developed and flown to collect, process, and preserve in-flight blood samples (fig. 9). The crewmen acquired approximately 11 ml blood samples with a conventional syringe and then transferred the whole blood into a pre-evacuated sample processor (fig. 10). The sample processor was then placed into a centrifuge to separate the plasma and cells and to transfer the plasma into a separate collection vial for preservation. This transfer operation had to be automatically accomplished while the blood was being centrifuged due to problems associated with weightless operations and fluid dynamics.

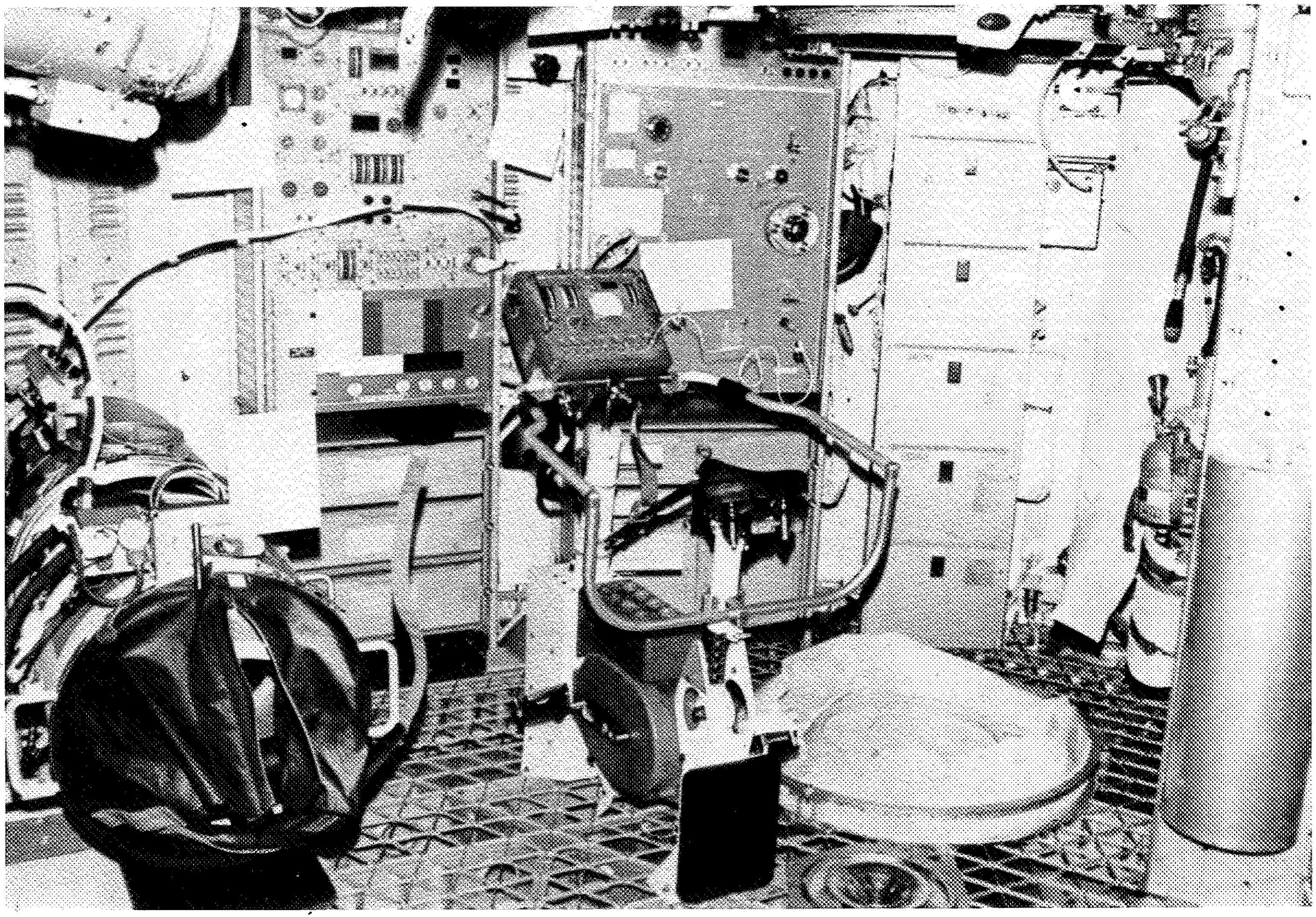

Figure 6. Photo of medical experiments from Skylab 3.

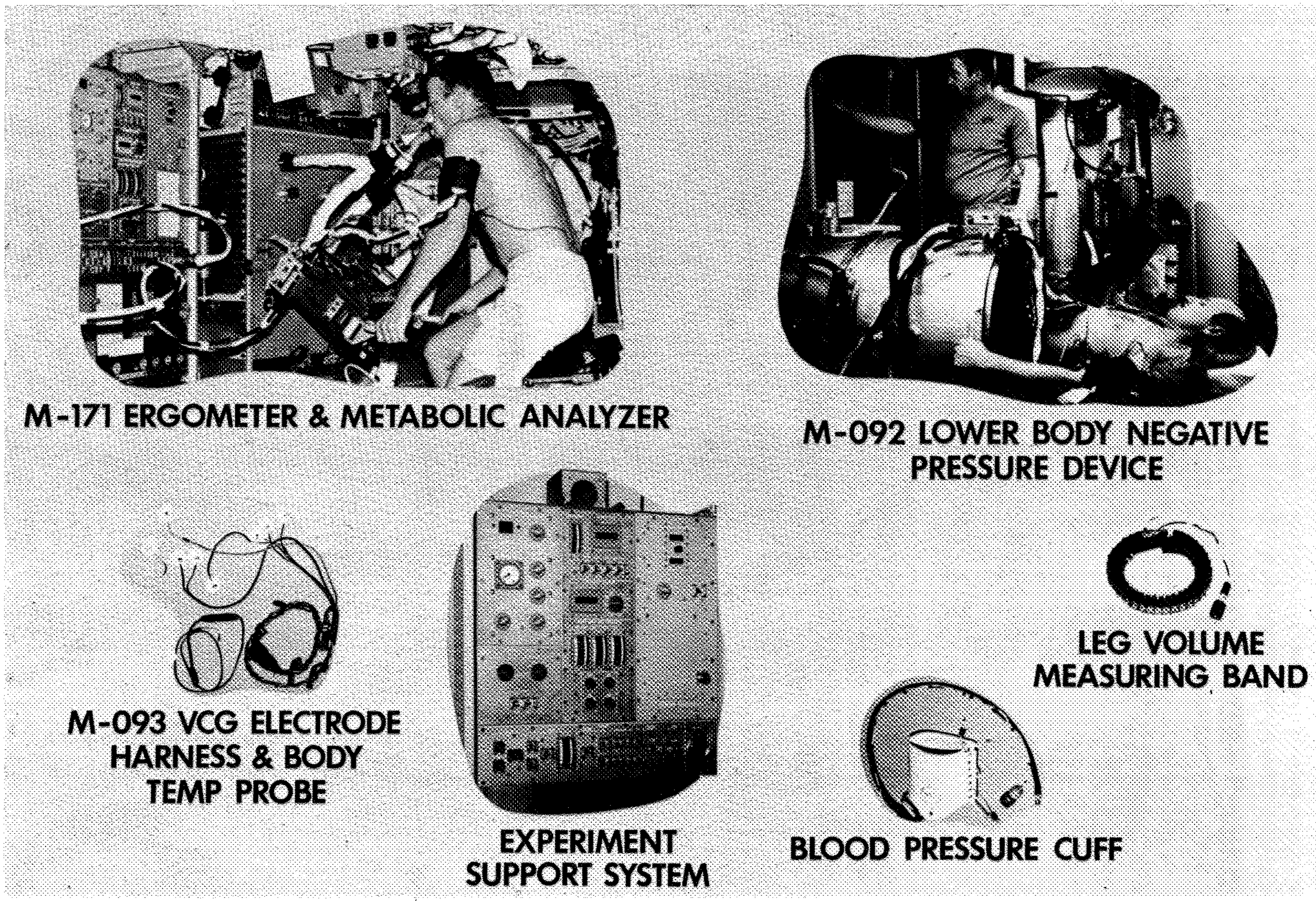

Figure 7. Skylab in-flight experiment equipment.

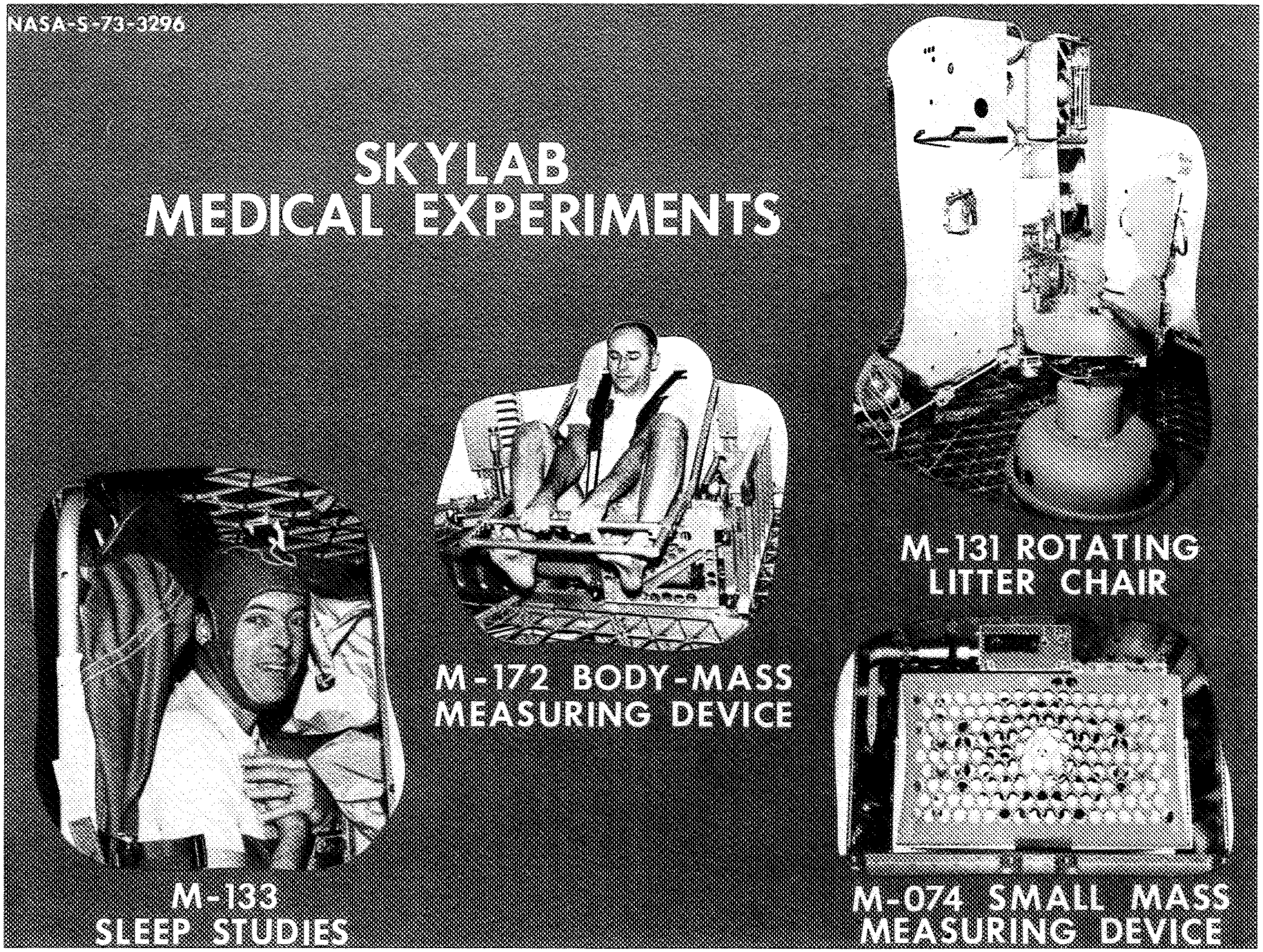

Figure 8. Skylab medical experiments.

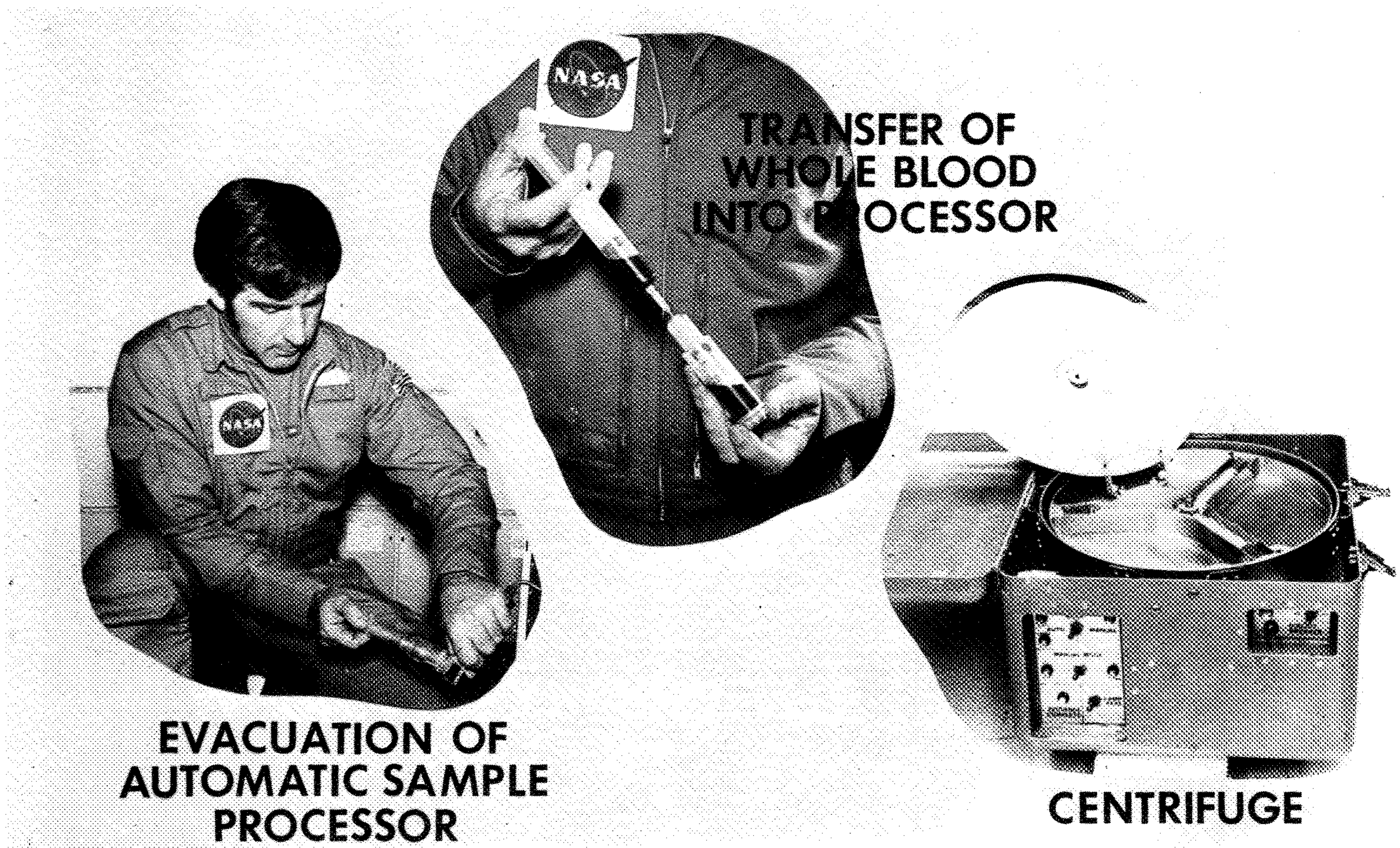

Figure 9. Skylab in-flight blood collection system.

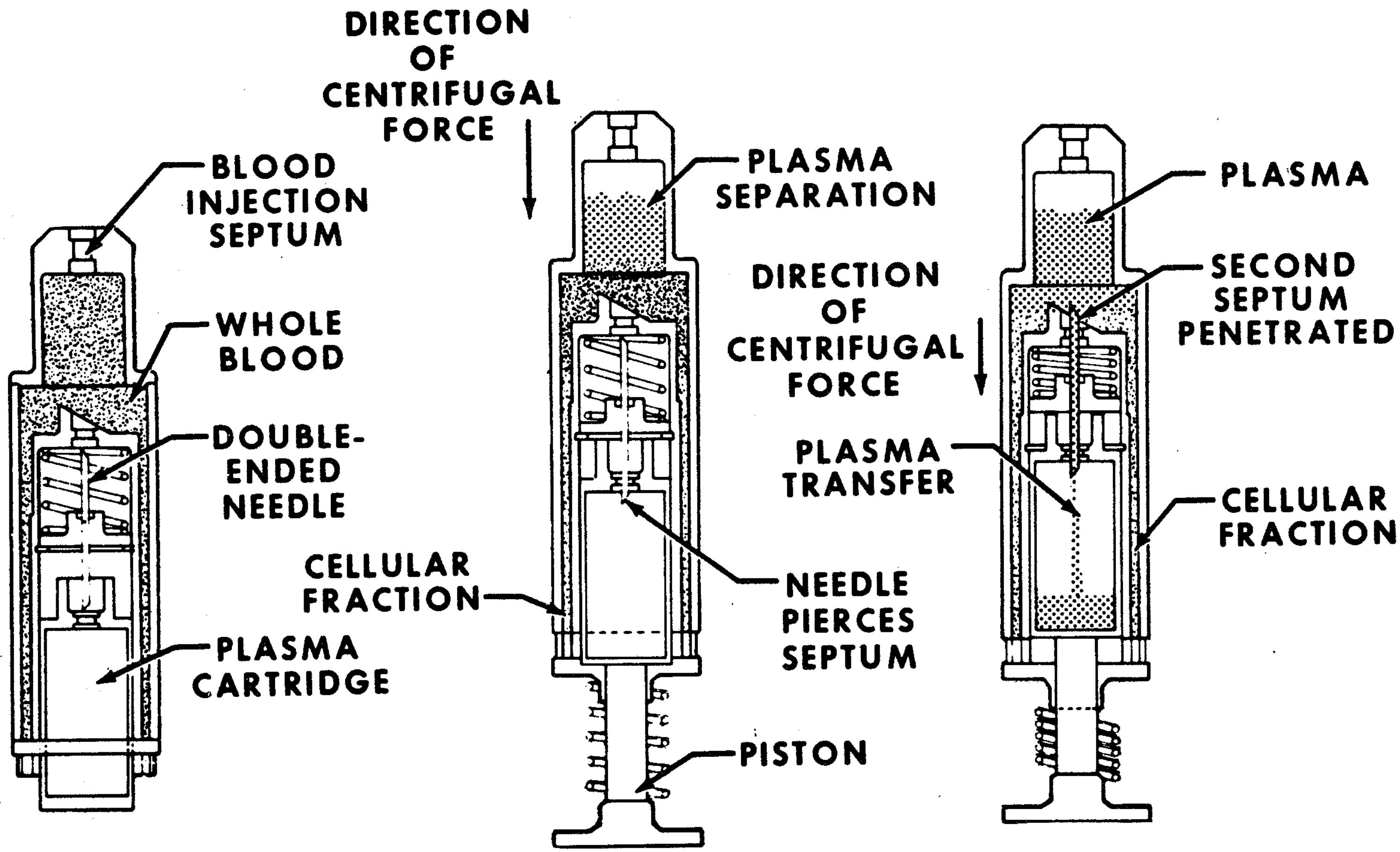

Figure 10. Skylab blood sample processor.

The cross sectional drawing of the sample processor shown on figure 10 illustrates how the equipment functioned. Whole blood was transferred from the syringe through a septum into the processor. A spring-loaded piston was attached to the bottom of the sample processor and the unit was placed in the centrifuge. Following initial centrifugation, the cells and plasma were separated. At this point, the centrifuge speed was increased to force the piston to drive the plasma vial septum past a needle and allow the plasma to flow into the vial. Following this separation process, the blood was placed in a freezer and preserved for postflight analysis.

The medical experiment equipment functioned without problems throughout the three flights. Medical data of high quality were obtained for all experiments. Vast quantity of medical data available for reduction and analysis was processed in an orderly fashion. This could not have been accomplished in a timely manner without computer processing. The quantity of information obtained from the medical studies conducted with the Skylab crewmen over a relatively short period of time is perhaps unique in medical research. Over 600 000 biochemical analyses were made on food, blood, urine, and fecal samples (fig. 11). In completing two of the major medical experiments, more than 18 000 blood pressure determinations were made and over 12 000 minutes of vectorcardiographic data were obtained.

SKYLAB MEDICAL OPERATIONS

The medical operational planning for Skylab was much more complex than any other U.S. manned space mission. The logistics planning required for crew feeding, sample collection, baseline experiment data acquisition, crew medical examinations, crew health care, data processing, and flight management into an integrated plan that meshed with program milestones required a major medical team effort.

The Skylab medical operations program was initiated in June of 1972 with a 56-day altitude chamber test (fig. 12) and was completed in April 1974 with the last postflight Skylab 4 crewmen evaluation tests.

The first launch was to place the Skylab orbital workshop in correct orbit; it was unmanned. The compressed schedule of the subsequent manned Skylab launches and the extension of mission duration after the first manned launch, Skylab 2, created an extremely heavy burden on the Skylab medical team. The medical experimental program was unique in that it not only provided scientific data, but, in turn, the data were used as the basis for operational decisions for the commitment to longer duration flights. This meant that at the end of each of the first two manned missions, the medical team had to make a recommendation for the

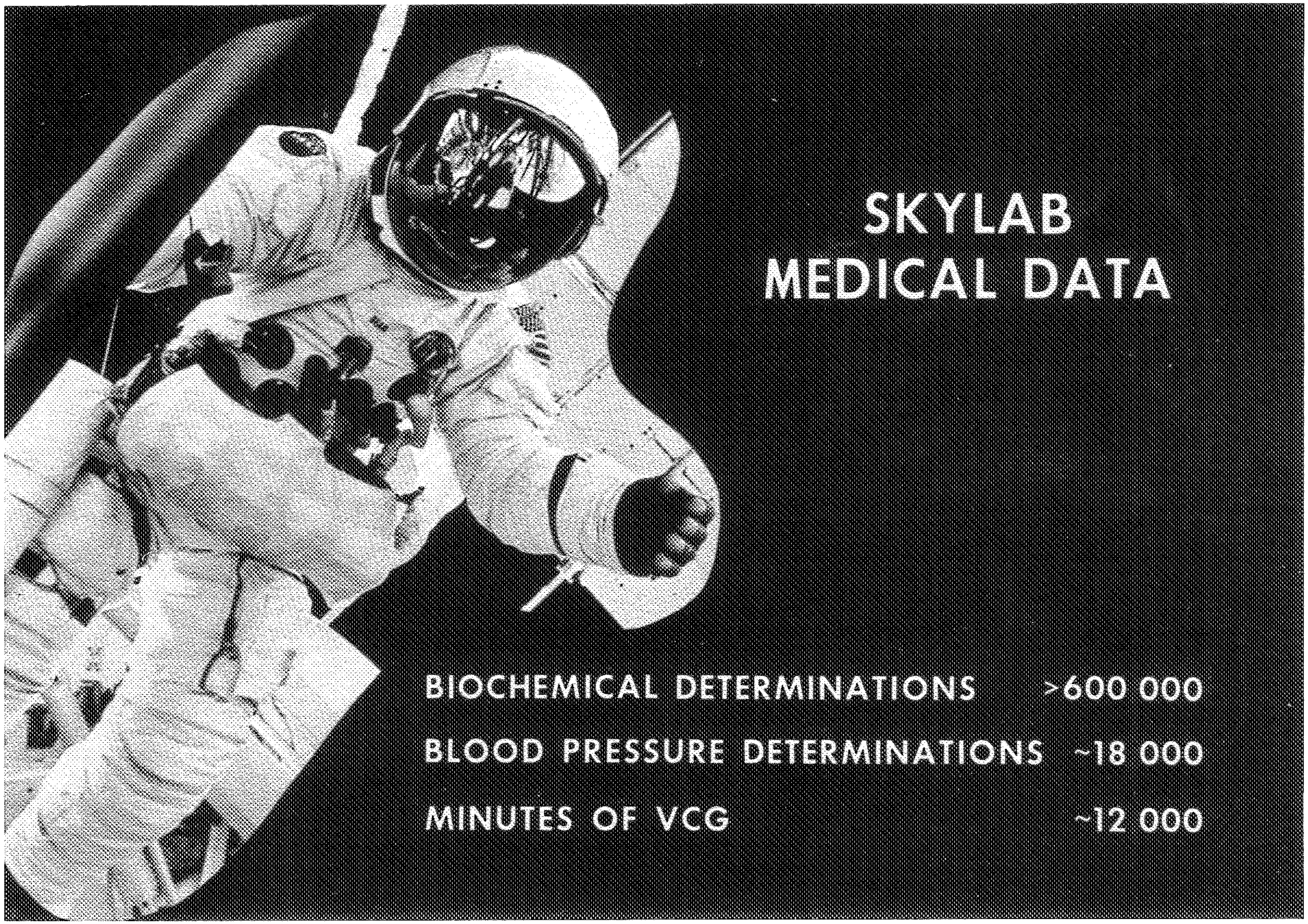

Figure 11. Skylab medical data.

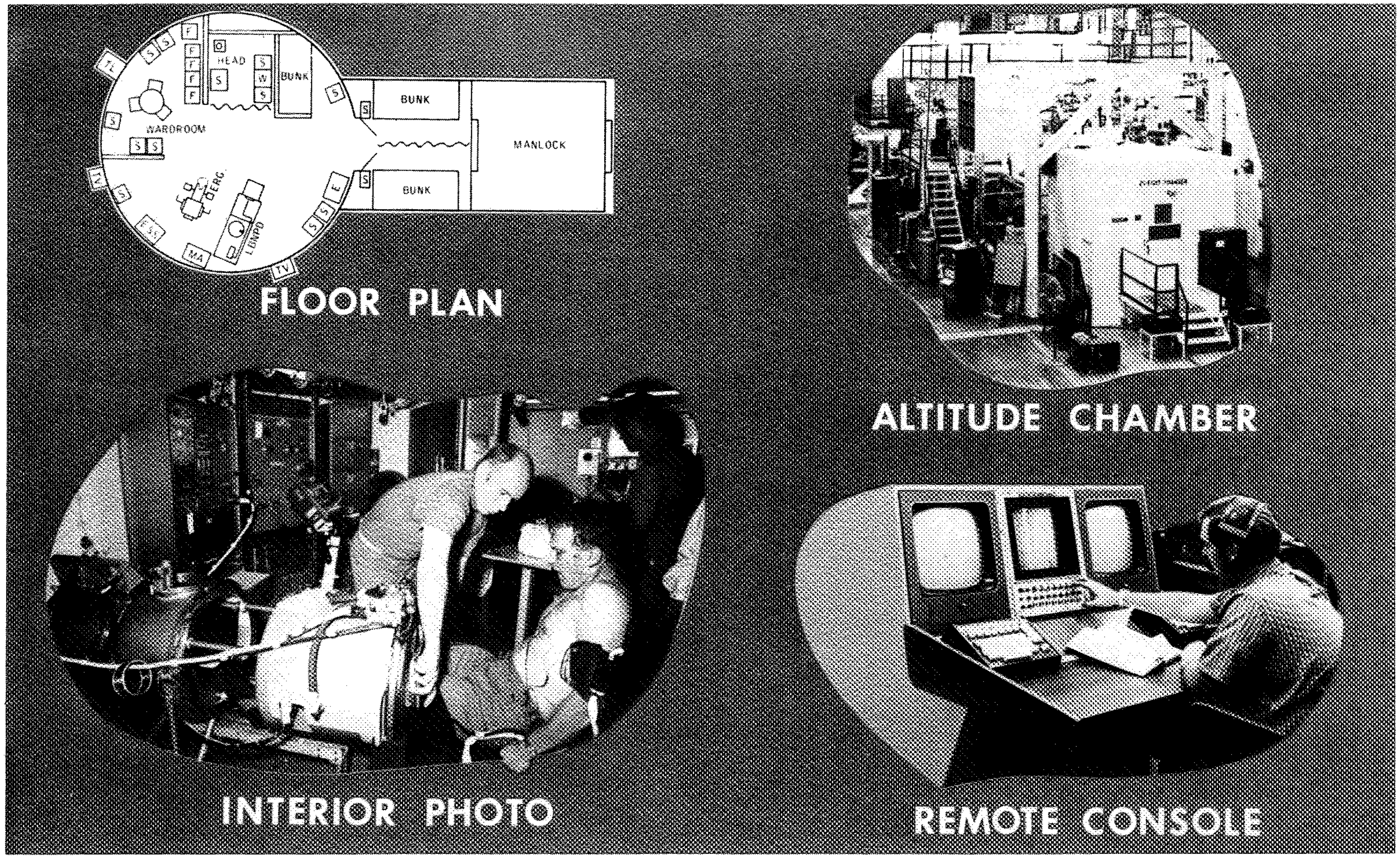

Figure 12. Skylab Medical Experiments Altitude Test.

extension of the next successive mission. From figure 13 it can be seen that the preflight phase of Skylab 3 started before the completion of the Skylab 2 postflight phase and after baseline data collection for Skylab 4 had begun. Skylab 3 was launched only two weeks after the Skylab 2 postflight studies were completed. Skylab 4 was launched only five weeks after completion of the Skylab 3 postflight medical studies. This quick turnaround required careful planning, establishment of priorities on samples and data processing, and the dedication and tireless effort of all members of the medical team.

Skylab Medical Experiment Altitude Test

The Skylab medical experiment altitude chamber test was a 56-day mission simulation conducted in a 6.1 meter (20 ft) diameter vacuum chamber. The interior of the chamber (fig. 12) was configured closely to the orbital workshop crew quarters level which consisted of the medical experiments area, wardroom, waste management compartment, sleeping quarters, and recreational areas. The atmosphere in the chamber was maintained at a composition identical to that of the orbital workshop with a 70 percent oxygen, 30 percent nitrogen mixture at 5 pounds per square inch (psia). Carbon dioxide levels were controlled at a nominal level of 5 mm Hg.

The prime objectives of the test were to acquire background data and to exercise the data management and processing techniques for selected medical experiments. Other test objectives included the evaluation of medical experiment and operational equipment, the evaluation of operational procedures and the training of support personnel under simulated mission conditions.

Like a flight mission, the test consisted of a 21-day prechamber phase, a 56-day chamber test, and an 18-day postchamber test period. All preflight and postflight medical protocols were performed with astronaut crewmen. The inchamber test portion of the program was carried out using full mission simulation procedures, and included: crew checklist, real-time mission planning, and data management. The communications with the crewmen were limited to a spacecraft communicator, as programed to be carried out in the mission. Simulated network communications were followed also, to evaluate the problems of lost communication between flight crews and mission control center, as they would be experienced in actural flight. A remote console was used by the medical team to develop and implement ground control procedures for flight. This test program was successful; the required baseline data were obtained and the encountered equipment failures and problems were corrected prior to flight. The ground support personnel became an effective team ready to carry out the complex flight program.

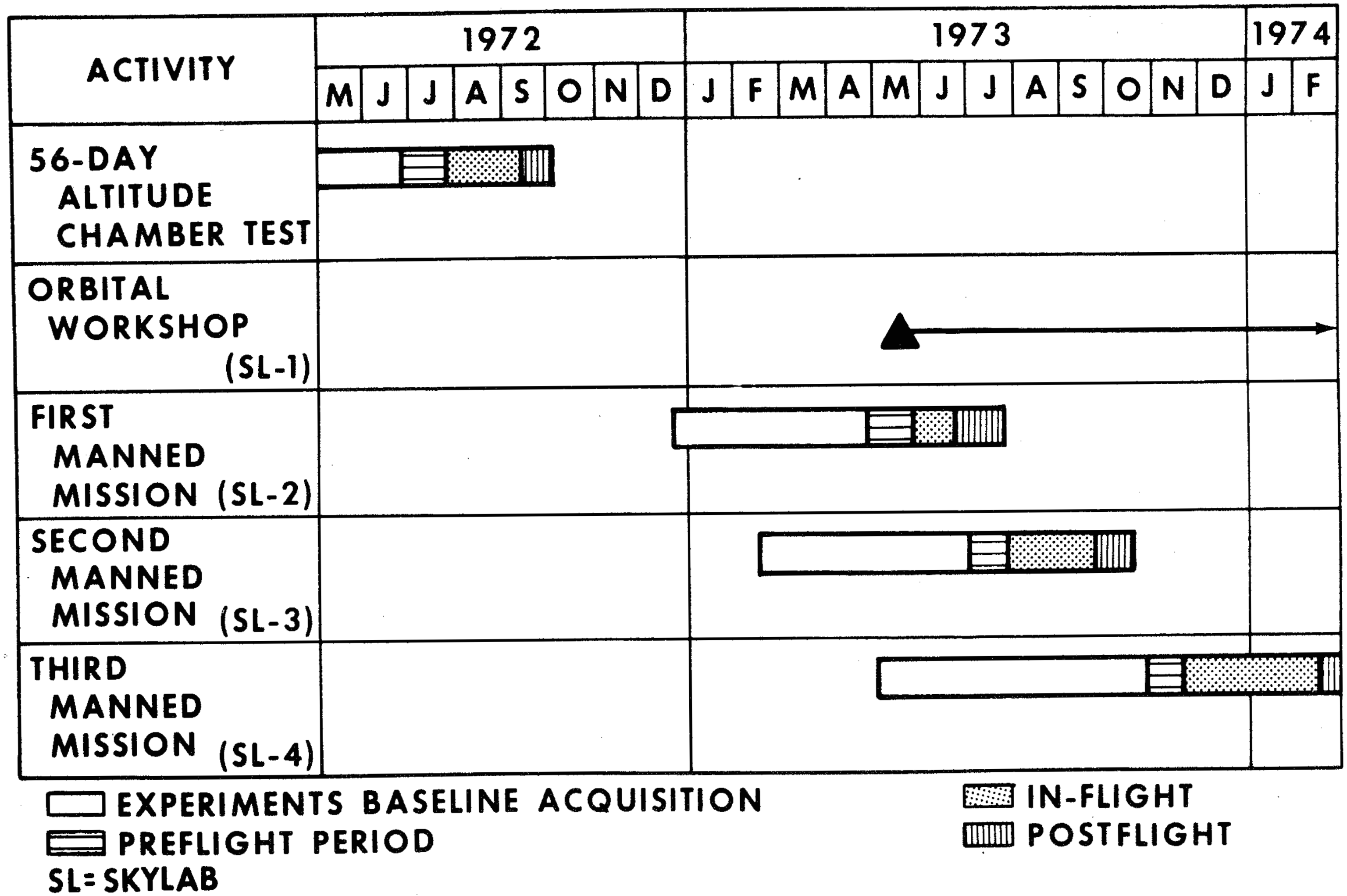

Figure 13. Skylab medical operations program.

Premission Support

The premission support for the first manned mission started in December 1972 with acquisition of the first baseline data for the Lower Body Negative Pressure (M092) and Metabolic Activity (M171) experiments. Additional baseline tests were conducted in support of the medical experiments at designated periods up to approximately one week from the launch of Skylab 2. These baseline data were primarily obtained in an orbital workshop one-gravity trainer (fig. 14). This full scale trainer contained fully functional medical experiments and other operational hardware. Combined crew training and baseline data collection were conducted with both the prime and backup crewmen. A remote medical console and data recording system was used to monitor the crewmen during training sessions and to train members of the medical team in control procedures and in the reduction of flight data. This combination training and medical baseline data acquisition was excellent for both the crewmen and medical experimenter. A comprehensive medical examination was given 30 days before scheduled launch to both the prime and backup crews and additional baseline data were obtained for the experiments.

Twenty-one days before launch, the crew was placed in semi-isolation to meet the requirements of the Skylab health stabilization program (fig. 15). The objective of this program was to protect the in residence flight crew from illnesses which might cause them to be removed from flight status and to preclude the occurrence of infectious disease in flight. All personnel who were required to work with the flight crews were designated as primary contacts. To protect the crewmen, these personnel underwent extensive medical examinations and immunizations and were required to report all personal and family illnesses. Those primary contacts who would come within direct contact (*i.e.*, 2 meters) with the crew were medically screened each day and were required to wear a surgical mask while in contact with the crew. Isolated crew quarters were established and personnel access into designated primary work areas was rigidly controlled. The Skylab health stabilization program was effective and no major problems were encountered.

During this period of isolation, the crew consumed foods identical to those provided from preplanned in-flight menus. Daily collections of urine and fecal samples were initiated. Medical examinations, microbiological and blood sampling, and experiment baseline testing were continued at the Johnson Space Center up to three days before launch when the prime and backup crews were moved to the Kennedy Space Center for the launch.

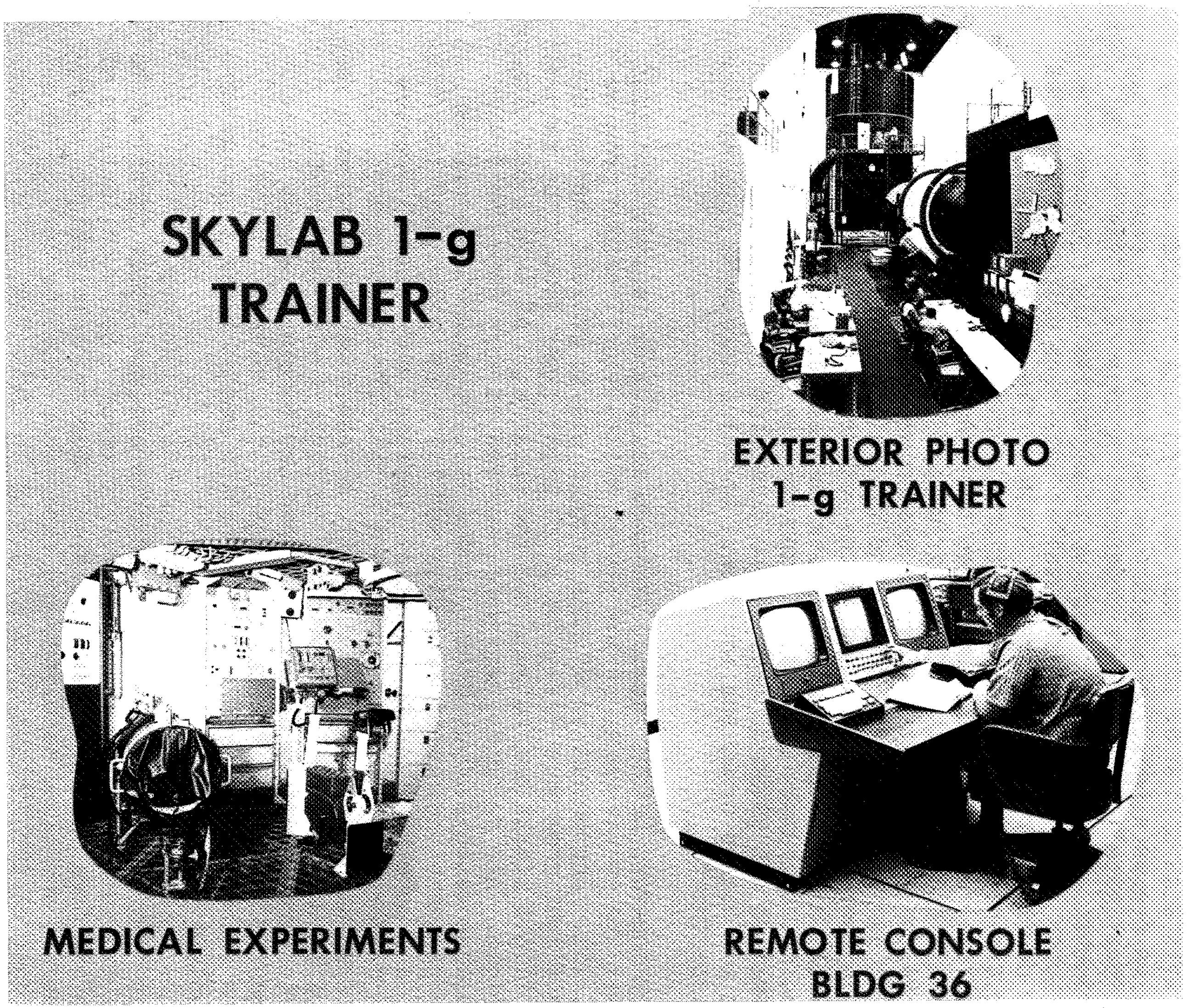

Figure 14. Skylab 1-g trainer.

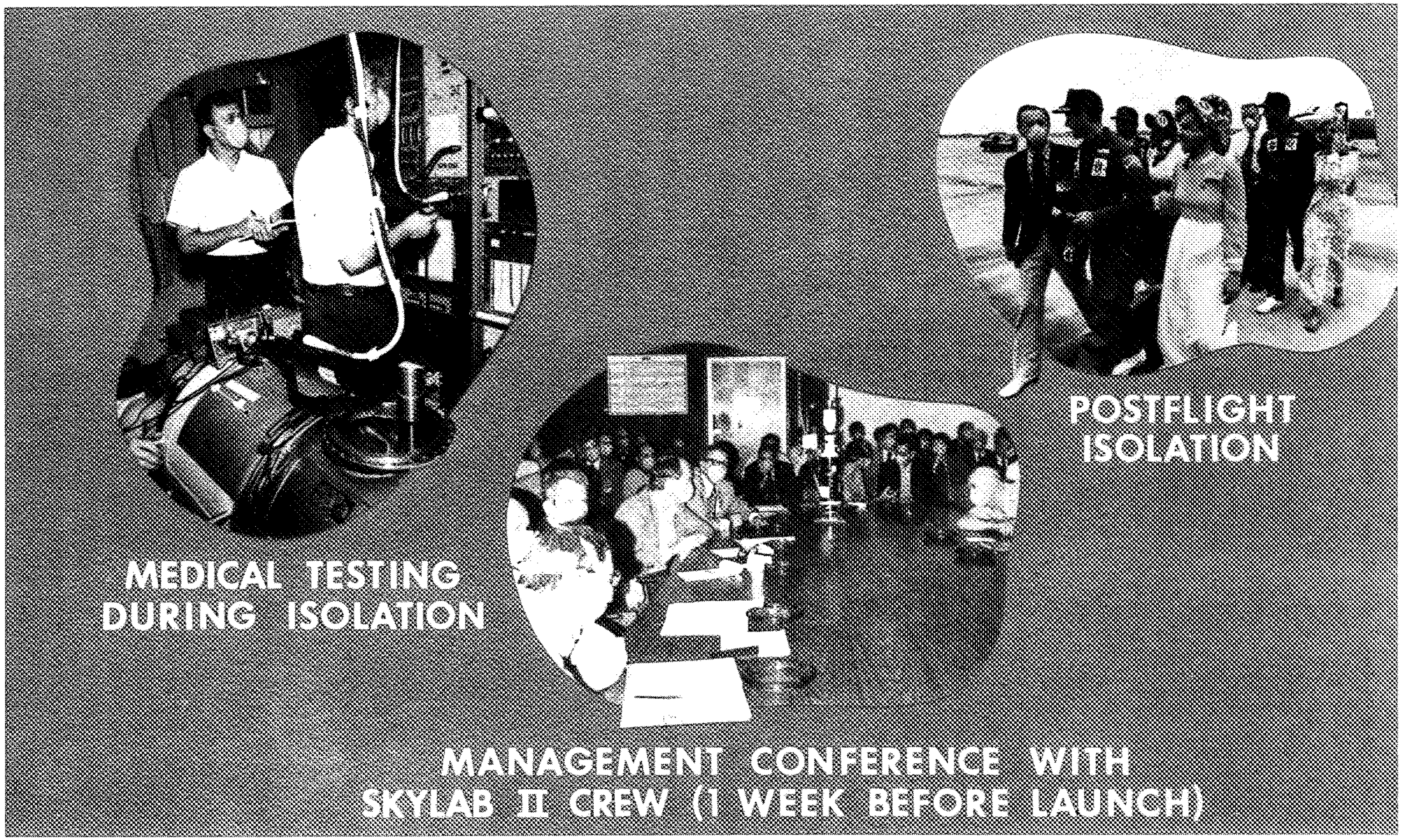

Figure 15. Skylab health stabilization program.

In-flight Operational Support

The management of the in-flight medical operations support and the necessary interactions with program management personnel, personnel representing the scientific disciplines, and the Flight Control Team were accomplished through a medical management group. The medical group met each morning of the mission to review crew health status, to evaluate the current status of the medical studies, to discuss equipment or other operational problems, and to establish changes in experiment priorities. Health trend charts were plotted each day (fig. 16) to provide experimental data which were useful in understanding crew health status. These charts included: crew weight, caloric intake, quantity of sleep, heart rate and blood pressure under dynamic stress, urine volume output, and other pertinent information. The Chairman of the Medical Management Group reported to a Flight Management Team on all medical matters and participated in operational decisions such as changing crew timelines, adjusting science requirements to insure maximum utilization of the crew and the current science opportunities, and to provide advice on major operational policy changes. This management scheme was extremely effective and was a key factor in the success of the Skylab program.

The in-flight activities of Skylab 2 are shown to illustrate the medical activities for a typical Skylab mission (fig. 17). The first two to three days of each mission were spent in the activation of the orbital workshop. These activities included such tasks as system checkouts and activation, transfer of equipment from the command module to the orbital workshop, changing air filters, *et cetera.*

In-flight medical monitoring of the crewmen started at launch through the use of an operational bioinstrumentation system (fig. 18). The crew was also monitored through the use of the bioinstrumentation system during all extravehicular activities. The frequency of in-flight medical experiments for the Skylab 2 crewmen illustrates when the various studies and/or samples were obtained in this mission. Throughout all Skylab missions, the Lower Body Negative Pressure (M092) and Metabolic Activity (M171) experiments were accomplished approximately every fourth day. Blood samples were collected weekly during the missions and biosampling was accomplished daily.

During the flight phase, real-time monitoring of the medical experiments was accomplished only when the spacecraft was over a tracking station. This meant, in some instances, there was a complete loss of communications with the crew and the telemetered data during medical testing. To overcome this problem, all experiment data were recorded onboard and subsequently telemetered through the tracking stations to the mission control center. Software programs were used to permit automatic

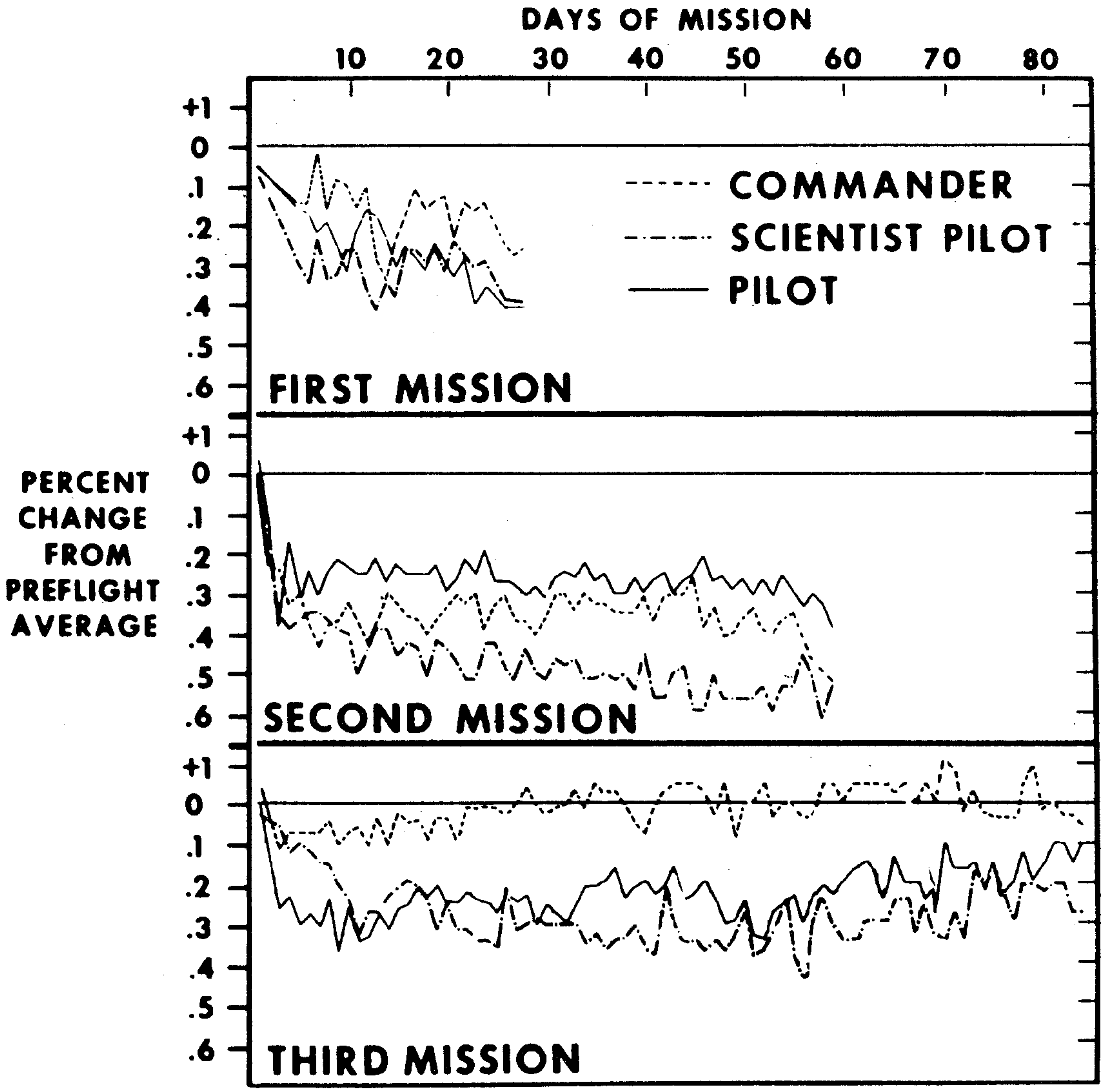

Figure 16. Skylab crew health trend chart - body weight.

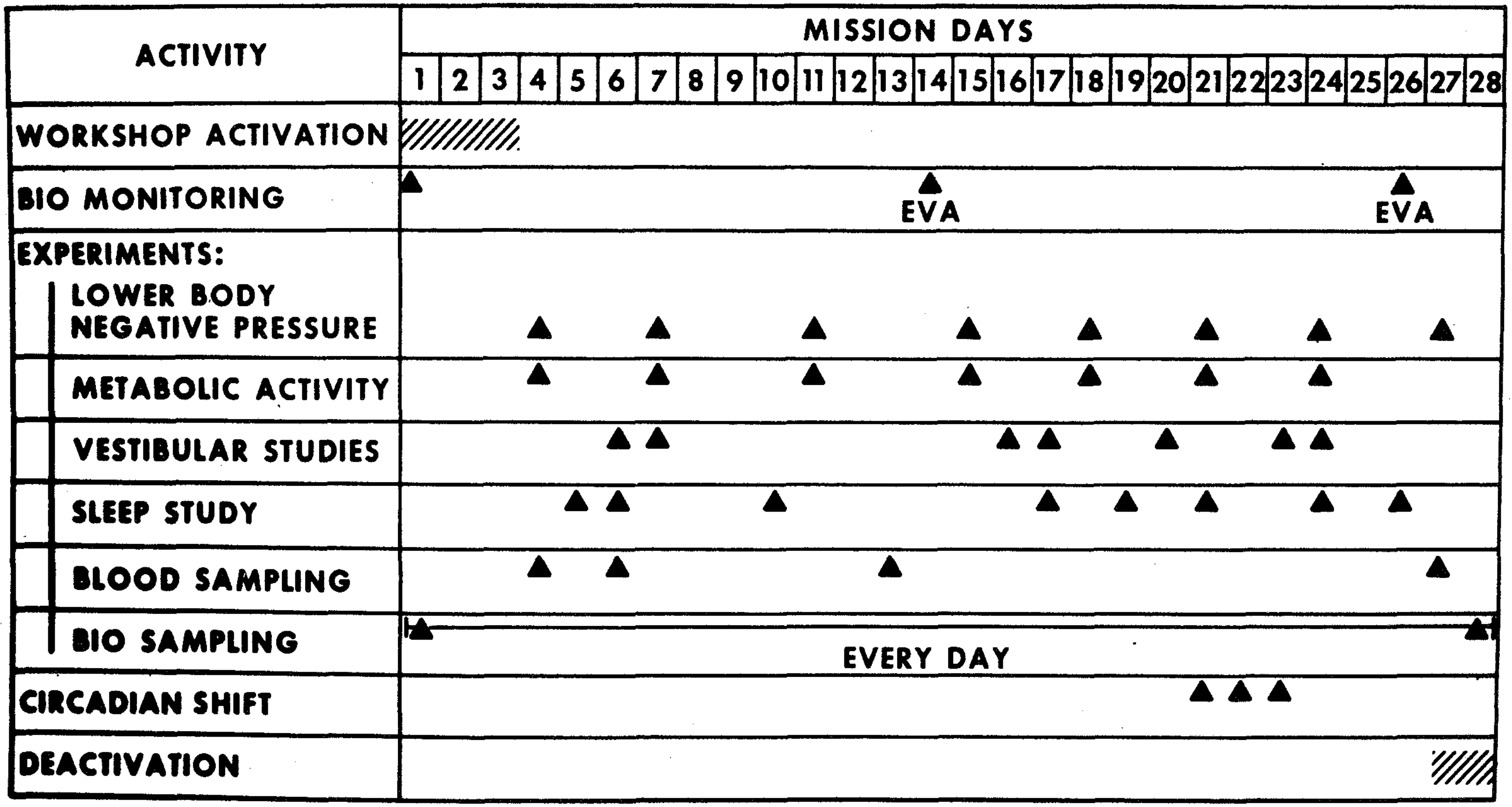

Figure 17. Typical in-flight medical activities.

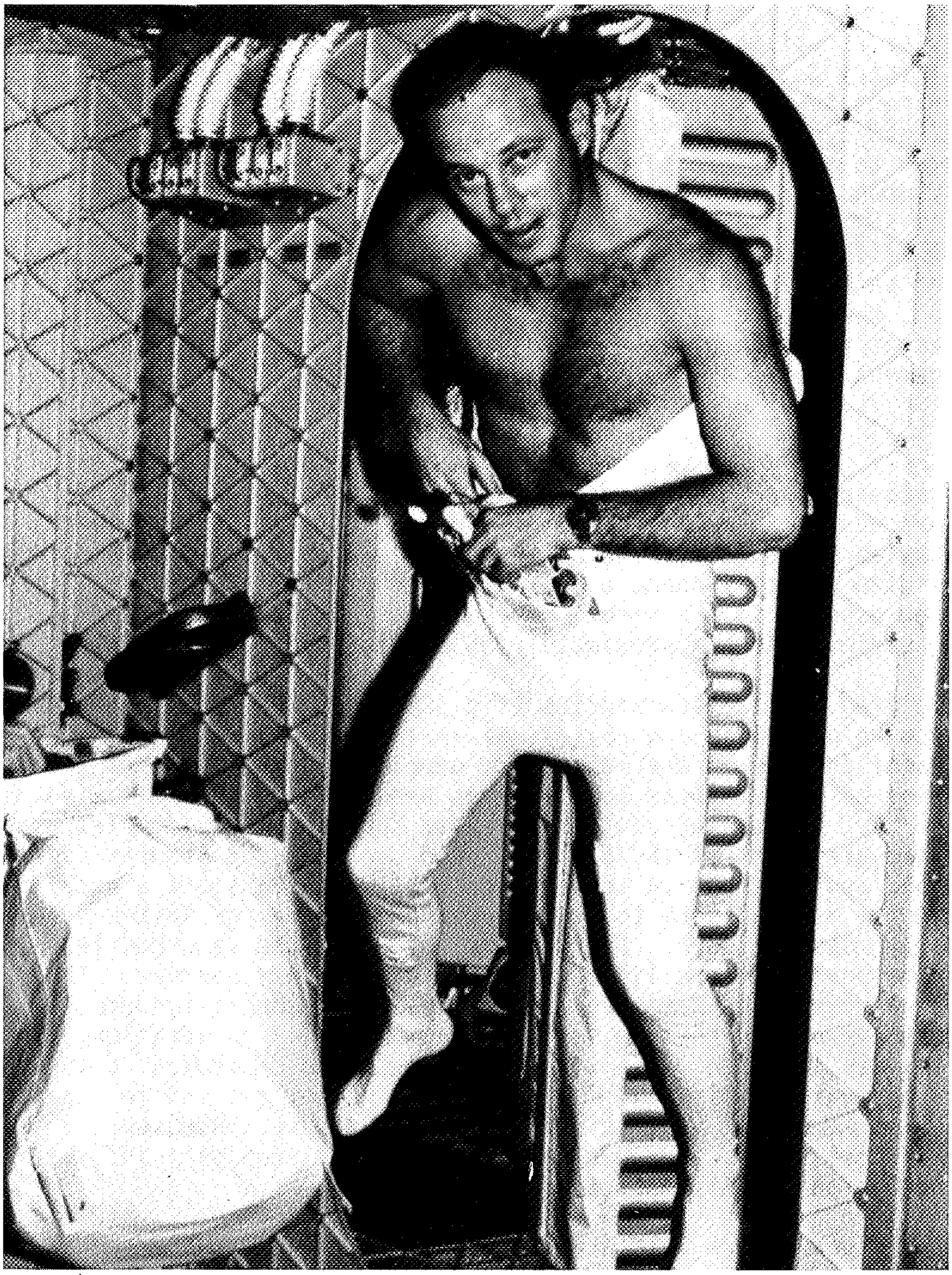

Figure 18. Skylab - operational bioinstrumentation.

computer reduction of the experiment data. The experimenters had a preliminary data printout within 24 hours after completion of an experiment test. During the last few days of all three missions, work/rest cycles were changed to adjust the circadian rhythm of the crewmen to the length of the pre-entry day and the time of spacecraft splashdown.

The in-flight portion of the three Skylab missions lasted 168 days during an 8-1/2 month period. Throughout this long and arduous period, the interest, enthusiasm, and concern for the crew was maintained at the highest level by all members of the medical and program management teams.

Postflight Activities

The recovery procedure used for the Skylab crewmen was altered from the procedures used in the Apollo program. Figure 19 illustrates the Skylab procedures. The Command Module and the crew were retrieved and lifted directly onboard by the recovery aircraft carrier. The crew egressed onto a platform on the hanger deck. Spacecraft and crew retrieval took approximately 35 minutes from time of splash.

Specialized mobile laboratories (fig. 20) were developed and equipped to acquire preflight and postflight medical experiments data. Six laboratories make up the laboratory complex. Photographs of the interior of two of these laboratories are shown on the left side of figure 20. The center photograph shows the laboratory complex as it was used preflight at the Johnson Space Center. The laboratories were designed and constructed to be moved in a C-5A transport aircraft to permit the medical team to cover contingency landings in the event of an early mission abort. For a normal mission, the laboratories were flown to port and were lifted onboard the recovery carrier. The mobile laboratories were designed with backup support systems, (electrical power, heating, cooling, *et cetera*). In addition, a data complex was included which permitted processing of medical data in a format compatible with the flight data. In use, the mobile laboratories proved to be useful facilities; they added to the convenience of the medical operations, they were operated without problems, and they provided high quality medical data.

Medical studies were initiated immediately after recovery operations. A summary of all postflight activities is shown in figure 21. The recovery day testing for Skylab 2 lasted for approximately 10 hours and included a comprehensive medical examination and the acquisition of data for all major medical studies as shown in figure 22. In subsequent missions, the length of the recovery day medical studies was shortened to reduce crew stress and fatigue from an overlong day.

Figure 19. Skylab recovery operations.

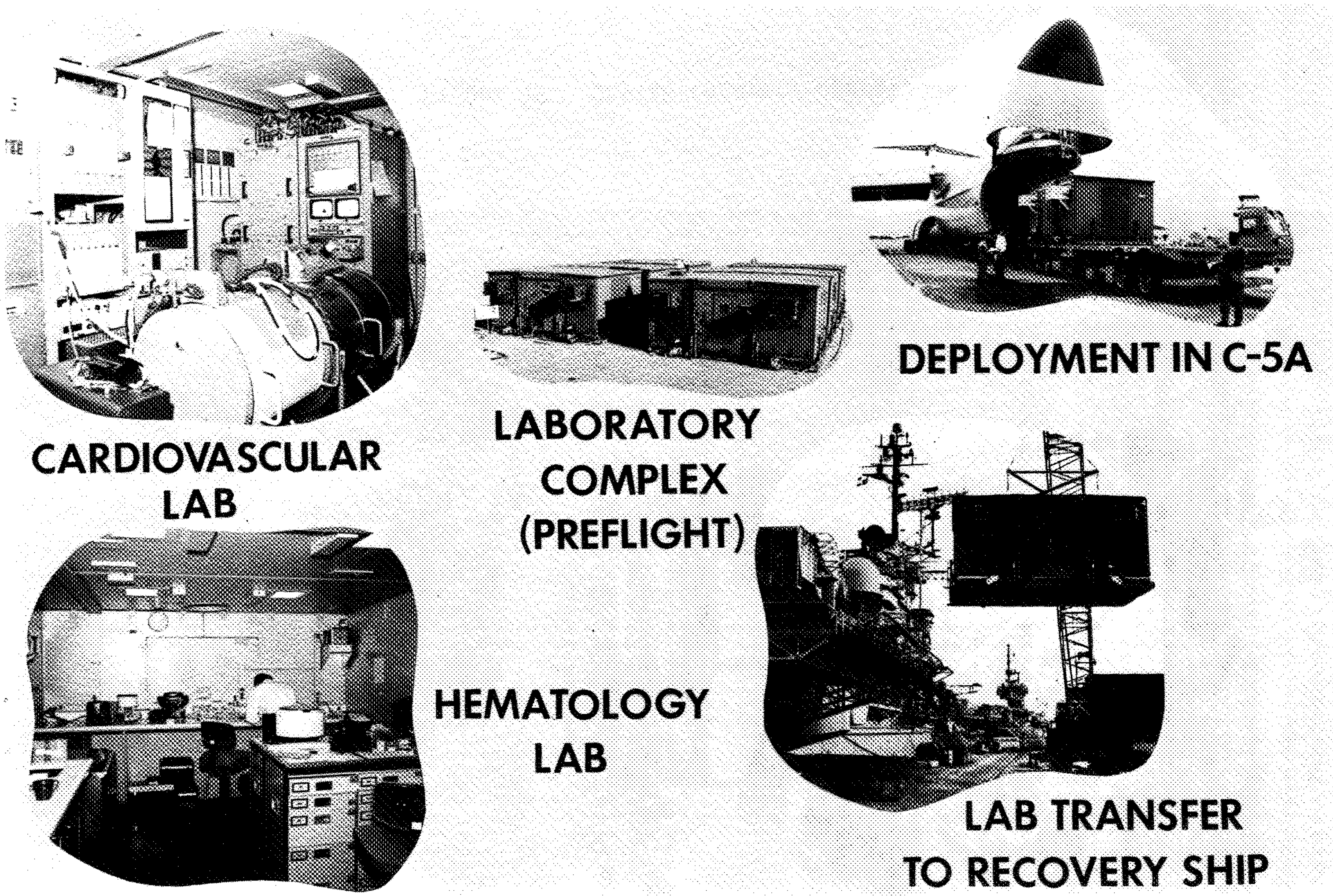

Figure 20. Skylab mobile laboratories.

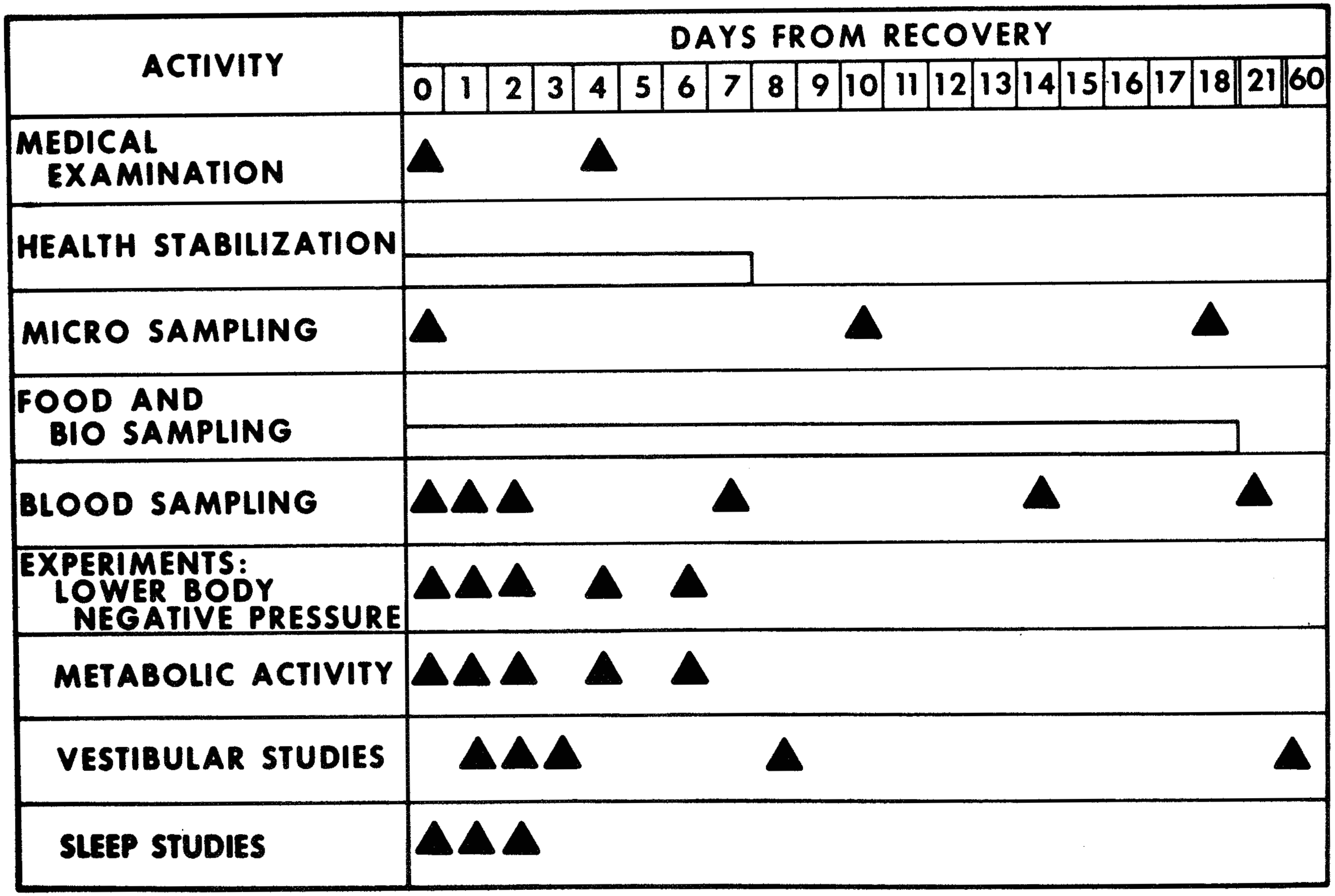

Figure 21. Skylab postflight activities (typical).

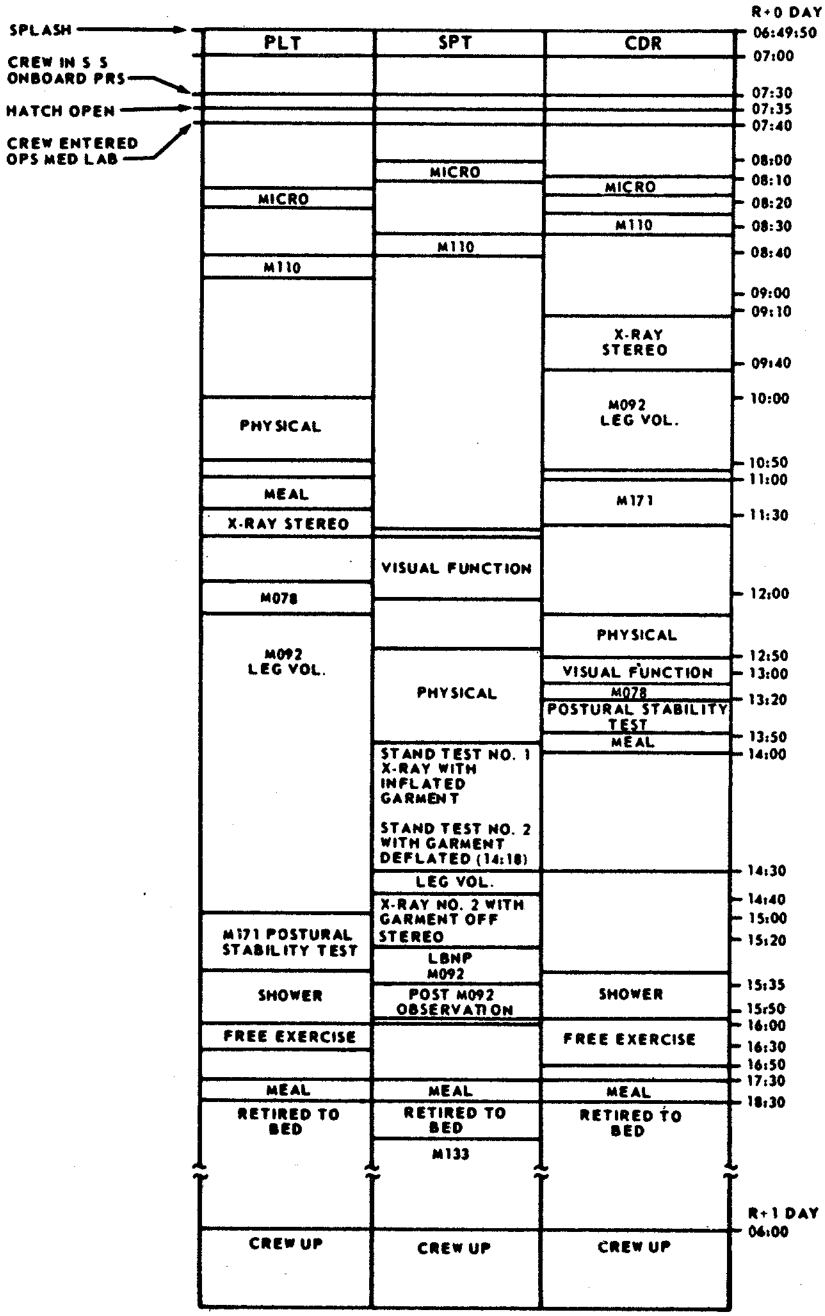

Figure 22. Skylab 2 recovery day medical testing.

The health stabilization program was followed throughout the first week following recovery to provide protection for the crew from infectious disease which might result from a depressed immune response after the long isolation period of the flights. Microbiological, blood, and biosampling was collected as shown. Medical studies were completed on the days shown on figures 21 and 22. In all Skylab missions postflight medical testing was continued until preflight control levels were reached.

OPERATIONAL EXPERIENCE

The launch of the orbital workshop on May 20, 1973, and the subsequent failures impacted the medical program. The loss of the micrometeoroid shield exposed the skin of the workshop causing an increase in orbital workshop temperatures and the partial deployment of the solar panels reduced the electrical power supply available for experiments and systems operation. The orbital workshop failure also caused a ten-day delay in the launch of Skylab 2. This meant that the health stabilization, controlled feeding, and biosample collection had to be extended. The exposure of the skin of the workshop (fig. 23) caused an elevation in both wall and spacecraft air temperatures. The plot shown in figure 24 illustrates the temperature increase for the early phase of Skylab; maximum temperatures in the food stowage area exceeded 130° F. In the ten-day period before the launch of Skylab 2, a thermal screen was developed which the crew could deploy to shield and insulate the orbital workshop. In the intervening time period, however, the increase in temperature caused several concerns to the medical team:

- First, would the foods be spoiled or changed by the elevated temperatures?
- Second, would other medical equipment be damaged by the increased temperatures?
- Third, would the polyurethane walls of the workshop be heated to a point where carbon monoxide or toluene diisocyanate be emitted into the spacecraft atmosphere?

Immediate action was taken to conduct ground based test programs or to develop equipment which the crew could use to understand and/or solve the problems.

Food test programs were initiated to study the effects of the increased temperature on microbial growth, food quality, and other characteristics. Identical foods were placed in thermal chambers; the temperature data from the workshop were used for a thermal profile. Periodic

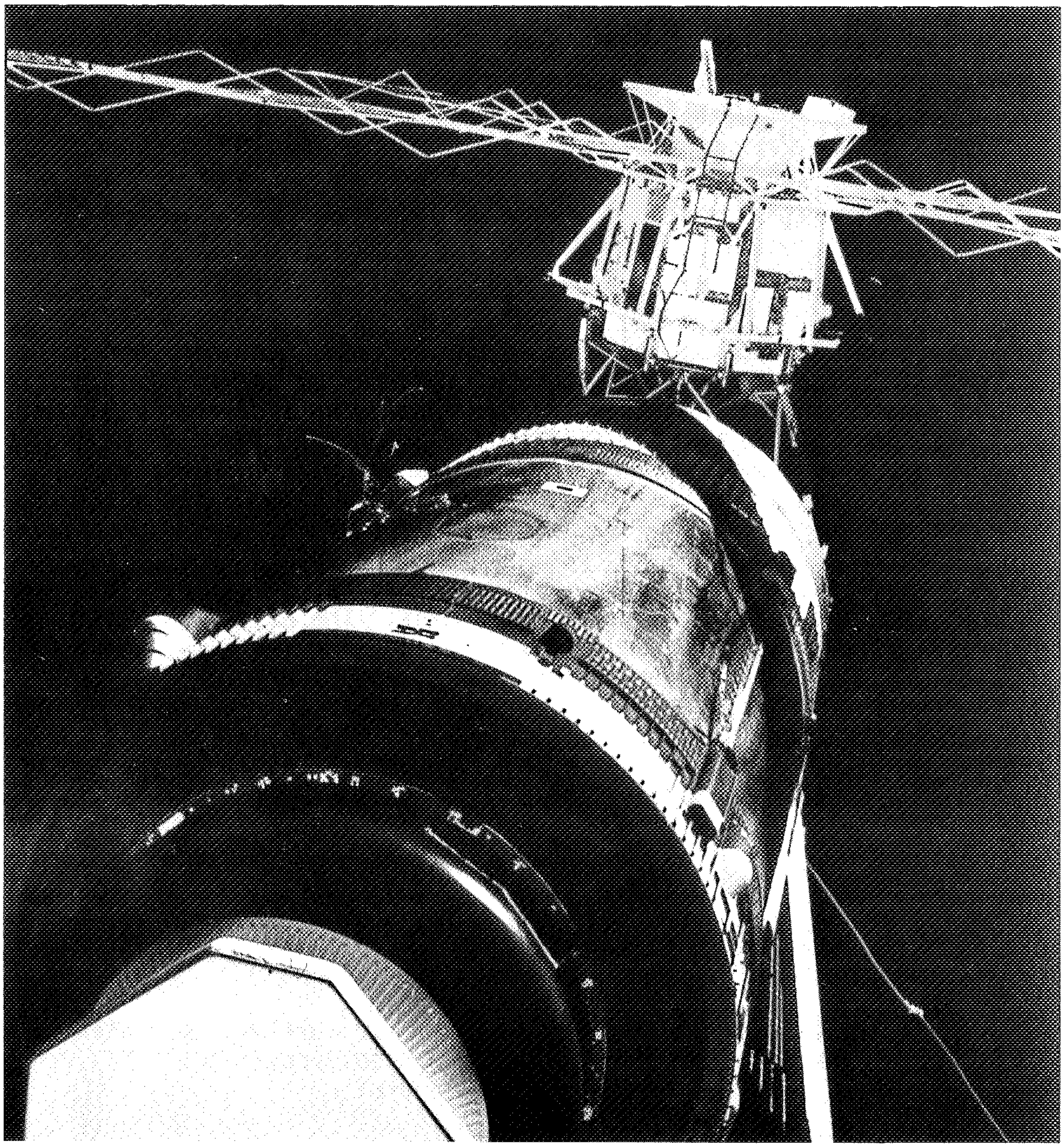

Figure 23. Damaged orbital workshop.

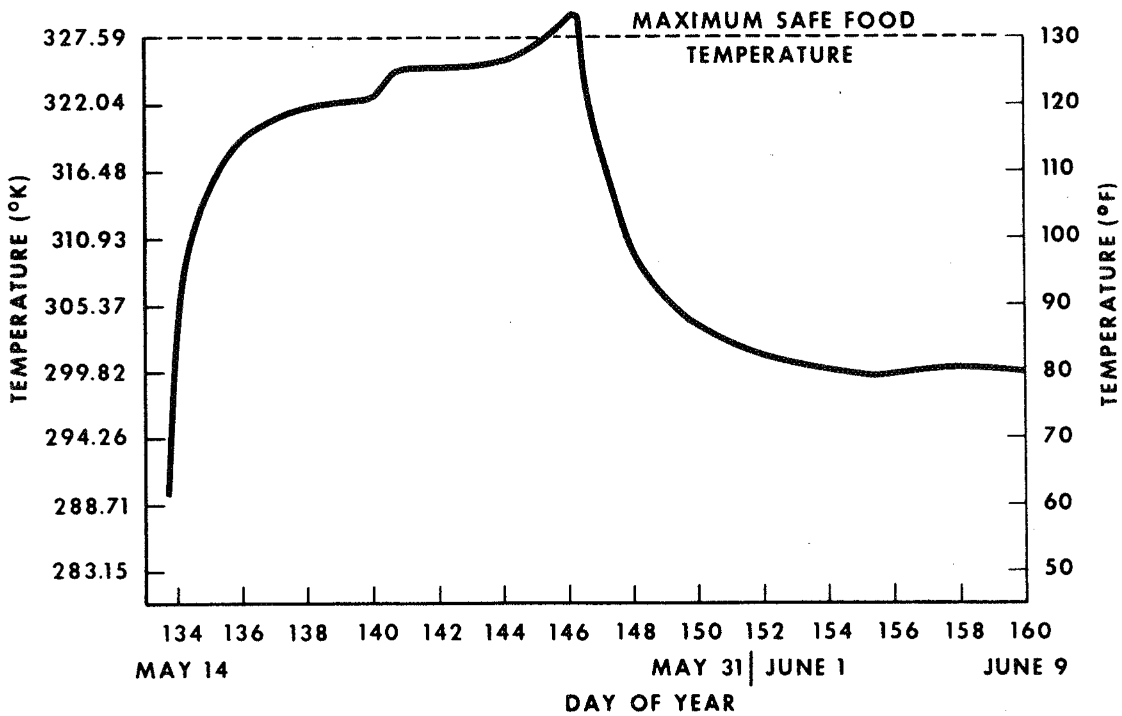

Figure 24. Dry food temperature profile.

food sampling was accomplished to determine biological and chemical composition changes, and the thermal effects on taste and palatability were evaluated. No significant food failures were encountered during these tests and the launch of Skylab 2 proceeded without major alterations to the food system. The food test program was, however, continued throughout the Skylab program and select food samples were returned from the three missions for analysis.

Similar thermal testing was accomplished for many miscellaneous medical items such as electrode sensors, sealed containers, *et cetera*. From these tests, it was determined that certain medications should be resupplied by the Skylab 3 crewmen. Additional procedures and equipment were developed to allow the crew to reconstitute the electroencephalographic electrodes on the sleep study caps.

The potential toxicity problems associated with the orbital workshop polyurethane wall insulation also was studied through thermal testing. It was determined that toulene diisocyanate and carbon monoxide could

have been present in the atmosphere. Special sampling tubes and adapters were built in the ten-day period between the launches of the orbital workshop and Skylab 2. The equipment developed (figure 25) permitted the crew to withdraw an atmospheric sample from the airlock and then the workshop before opening the hatch into these areas. In addition, special masks were provided to allow the crew to move into the orbital workshop if the toluene diisocyanate and/or carbon monoxide levels so dictated. The Skylab 2 crew found no toluene diisocyanate and the carbon monoxide concentration was less than five parts per million. The toxicological aspects of the Skylab program are covered in more detail in a subsequent paper in this Symposium.

The crew deployed the first thermal screen on the second day of the first mission and immediately the orbital workshop wall temperatures started to decrease. Within several days, the ambient gas temperature had dropped below 80° F. The elevated temperature in the workshop did delay the start of some medical experiments and, no doubt, influenced the results of the first medical studies. However, through the ingenuity of man and the efforts of the Skylab 2 crewmen, the mission and the workshop were saved from what appeared to be an obvious total failure. Subsequently, the Skylab 3 crew deployed an additional thermal screen (fig. 26) to further protect the orbital workshop againse excessive heat changes for that mission and for Skylab 4.

Throughout the Skylab flight program, alterations in equipment and procedures were made for each suceeding mission to capitalize on the flight experience of the previous mission. The Skylab 2 crew recommended that the personal exercise program in-flight be expanded in both duration and type. To meet this recommendation, the exercise period for the Skylab 3 crew was expanded from one-half hour to one hour daily and an additional exercise device was launched with the crew of Skylab 3.

On Skylab 4, the duration of crew exercise was further expanded to one and one-half hours daily and a unique treadmill device was used by the crew. In addition to these equipment-associated changes, additional scientific studies were added to the programs for both Skylab 3 and 4. The results of these studies are presented in other papers in this Symposium Report. These additional studies demonstrate the flexibility afforded the medical team and the support given to this team by program management and the flight crews.

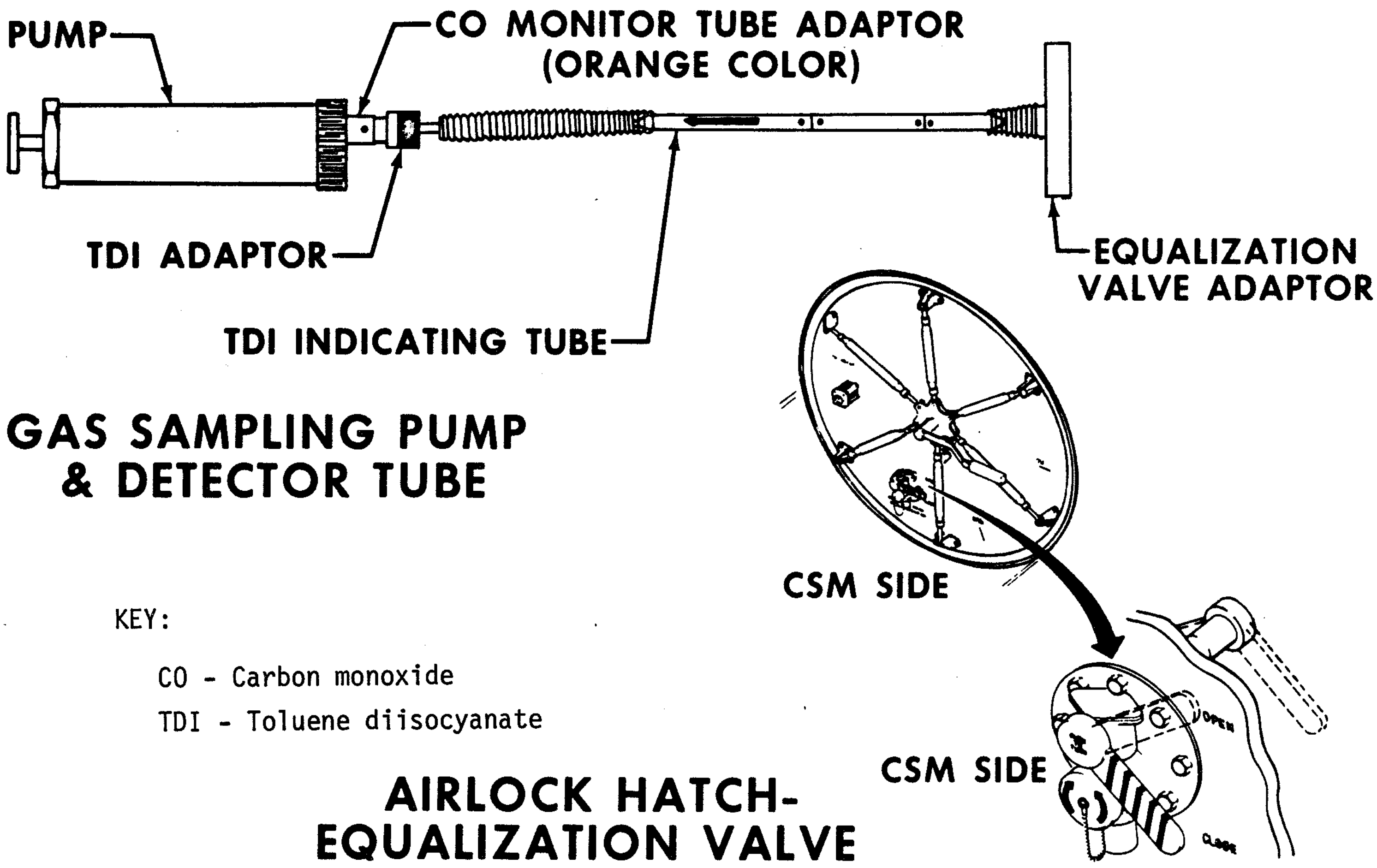

Figure 25. Skylab 2 gas sampling equipment.

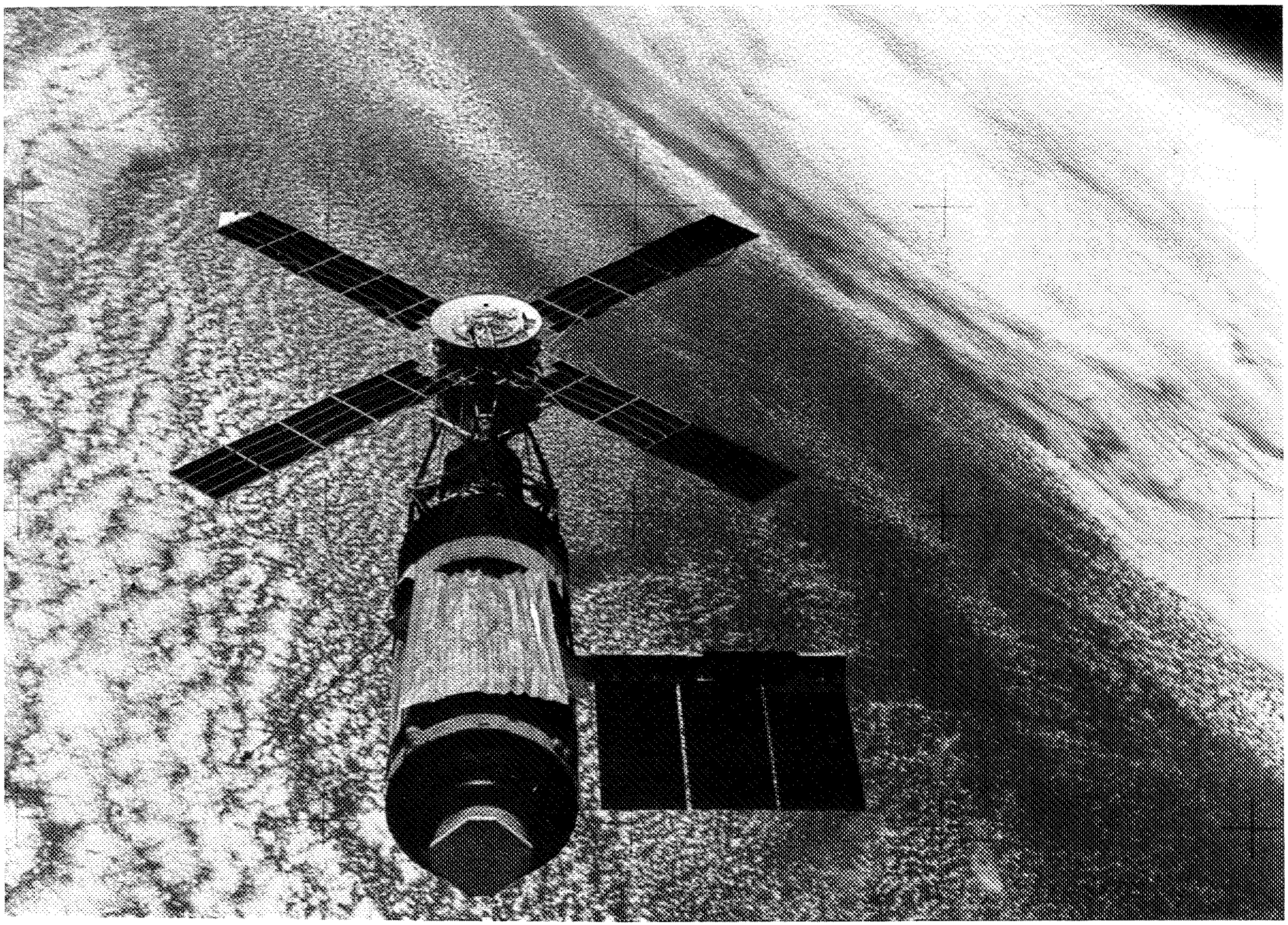

Figure 26. Orbital workshop with thermal shields deployed.

CONCLUSION

The Skylab Medical Program met or exceeded all of the planned objectives. The medical operations were conducted without any major problems and the medical equipment functioned flawlessly. The medical data received from the crew were of excellent quality. The quantity of information available from these three missions is staggering when viewed in its entirety, however, the investigator team has done a commendable job in presenting these results only six months after the last Skylab mission. Some investigators, no doubt, still consider their results preliminary and the Skylab medical team must still attempt to integrate the results of individual studies to give a more comprehensive understanding of what these data really mean. Skylab represents a significant milestone in the development of space medical knowledge. From the information to be presented at this Symposium, we feel confident that man can fly longer missions as required for future space exploration. The Skylab crewmem have demonstrated the versatility and ingenuity of man to make repairs, to carry out observations, and to conduct scientific studies.

Those of us responsible for the Skylab medical program are proud to have the opportunity to present this Symposium and hope that we do justice to the outstanding accomplishments of the Skylab crewmen.

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FLIGHT CONTROL EXPERIENCES

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JOHNSTON: Our first papers this morning are going to be flight crew reports. Our first speaker is Dr. Story Musgrave. He's an astronaut physician; he was the backup Scientist Pilot for Skylab 2; he was one of the astronauts instrumental in following many of the developments of Skylab medical equipment; and he also served as the spacecraft communicator for Skylab missions two and three. Dr. Musgrave.

MUSGRAVE: Thank you very much, Dick. I am going to give you about a five minute briefing this morning on the biomedical aspects of mission control; or, you might entitle it, "The Management, Direction and Support of In-Flight Biomedical Activities". I'm not a manager, and I'm not a director; I hope I did support. So you'll see in places that I'll have my own perspective. It's a great pleasure to address you today. The work of ground support and CAP COMM are great; flying is even better. But when one has got a flight on, the next best thing to it is the support on the ground.

As Dick Johnston mentioned a little bit earlier, policies and decisions were made, as far as medical aspects go, by a multidisciplinary medical-managment team early every morning. Other persons concerned with flight control were the flight surgeons, which you'll hear from later, and the biomedical officers. A member of each of these two groups occupied adjacent consoles in the Mission Operations Control room. In general, the flight surgeons were concerned with crew health; the biomedical officers were concerned with the operation and collection of experiment data. However, they did have many overlapping functions. In support of them and other activities, we had a biomedical science support room consisting of between 4 and 12 scientists and technicians who:

- retrieved and compiled
- helped to build the flight plans
- and made inputs to the flight plans and the medical experiments checklists.

On each mission, at least one of the CAP COMMS was a physician astronaut. Theoretically, this should be a plus for medical science. However, since I was one of them, I won't pass any judgement on that.

In the Mission Operation Control Room and in the science support room, we had multiple displays of real-time or recorded data from the bio-instrumentation that were obtained, say, during launch, extravehicular activity, entry or other critical parts of the mission. Also, we could display any of the medical experiments data on a real-time basis simply by punching a keyboard and calling up this information either in digital or graphic form from the mission operations computers. The information one might get later from recorded data would seem to be very similar -- almost identical to that which one receives in real-time display; it's somewhat similar to going to a football game or watching the game on television.

Daily, we built a flight plan; that is, a plan for the crew to tell them what to do on a given day. What would their on-orbit activities be on a given day? Program Director Bill Schneider alluded to this earlier today. With many people calling him and asking him to get certain things on the flight plan, he was somewhat like a worm in a nest of robins. The flight plan was constructed from approximately 150 experiments depending upon such factors as: the frequency requirements of the individual experiments, and the orbital characteristics for that given day. When was the Sun available? When was the Earth available? What was the Earth track? Other constraints arising from the particular experiments to be run: Were they compatible with each other? One needed two men to do Earth resources; one needed two men for most of the major medical experiments; therefore these experiments couldn't be run together. What was the Sun doing? Did we have priority to study the Sun? Was it a particularly active Sun or a Sun in which the data that would be gathered on that particular day be extremely important? So, at first, the science planning and the flight planning were based mostly on mission rules that had been established beforehand with some form of priority for experiments. But, during the first mission, we, and that's a collective "we" meaning JSC flight controllers and managers, developed what was called a science-planning meeting, in which they would plan the next week's activities taken from the collected inputs and requirements from all the different disciplines, such as the solar physics, medical, Earth resources, the corollary experiments, astronomy experiments, and the like. They would have pooled in this one place, the requirements and the desires of all the different disciplines, and then, with representatives of all the different disciplines assembled, they would go through a series of trade-offs in which they would measure one against the other and try to arrive at an optimum flight plan. In this way, the Earth resources people could listen to the solar physics people and listen to their pleas about how important it was to get this particular Sun on a given day; or the Kohoutek people -- the comet people, could listen to the Earth resources people say, "This is the only time we're going to get

over this site; we haven't seen this particular site once yet during the Skylab mission". And so the different disciplines could listen to each other and could trade off against or for the other and hopefully arrive at an optimum flight plan.

Early Skylab crews demonstrated tremendous efficiency. They got way ahead of the time line of what was expected preflight that they would be able to get done. They were getting more and more done. In fact, shortly they began to ask for more things to do. While we had many vehicle-type constraints and many experiment constraints, we ended up with more and more free crew time. So on a real-time basis, we started to devise what we called in the medical world (and in some others) DTO's (detailed test objectives). In other words, we came up with new experiments, and we did this in three different ways. One, is simply to change the protocol of a given experiment. It would be the same experiment, but you'd change the protocol to get some different data. Two, is to come up with a brand new experiment, a new way of using existing hardware. And three, is simply to make new observations that didn't require new hardware. Many of the presentations that you'll hear during this symposium concern data collected in this sort of way. These were brand new ways of collecting biomedical data that had not been planned for in advance, and they were done in real time. These kinds of real-time changes to the flight plan and the checklist were accomplished by getting Principal Investigators together with our procedures people who build our checklists to come up with a revised checklist or procedure. And we astronauts go into simulators, such as our one-g trainer, with all the medical experiments and others and actually fly these procedures in there. We run them in the simulators to see that they are workable and put the polish on them prior to sending them to the crews on board the spacecraft.

Every evening, we received a report from the flight crew regarding such things as; their water gun readings, their body-mass-measurement-device readings, and their food-consumption status. Then, every evening in addition to this private conference with their own flight surgeon we would send up to them a medical status report which contained a summary of the data that was obtained the last time they ran the medical experiments, such as lower body negative pressure and the bicycle ergometer. It included things such as their body weight, their water consumption and the number of calories they consumed, and also any mineral-type supplements that they would have to take the next day to stay on the mineral balance.

Lastly, on a weekly basis, we had an open-loop conversation with the crew and one of the scientists from the medical science community. This representative would give the crew a summary of the medical data

that was being obtained from their mission; he would state the trends observed; he would compare those with medical data from previous missions, such as Gemini, Apollo, or previous Skylab missions; and he would give them an idea of the significance of this data. Probably the most important benefit of this conference was that it served as a general colloquium on space flight physiology and medicine with the crew on a real-time basis.

SKYLAB 4 CREW OBSERVATIONS

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JOHNSTON: The next paper will be "Skylab 4 Crew Observations". Dr. Ed Gibson, a scientist astronaut who was the Scientist Pilot on Skylab 4, will make this presentation. Ed is a specialist in solar physics and I think that he was extremely enthusiastic about the ATM and the conduct of that experiment in his mission.

GIBSON: Thank you. I'd like to first point out that for us the ATM observations and the medical experiments were very enjoyable aspects of the flight. We got involved in the understanding of the objectives of the medical experiments and could see some of the progress, some of the changes and some of the things which one is looking for during the conduct of those experiments. So, for us, they were extremely interesting. They were also enjoyable from the standpoint of the people with whom we worked. They were very cooperative during the initial training and during the flight itself. We felt that the medical folk were always behind us in two ways: in getting the data as well as making sure that we were in a reasonable condition to carry out all the other objectives of the mission.

Now, what I'm going to state is essentially how we looked at it from Skylab 4, and I'm going to do it from the standpoint of a person with a background in engineering and physics. I was appointed as the ship's doctor, which made the other two guys feel rather comfortable. I'll mention just several areas and not go into them very deeply: food, exercise, scheduling, medical training, the effects of the fluid shift, vestibular effects, and several miscellaneous items.

First of all, the food area. We experienced hunger on two different occasions because of the types of diet we were on. In order to extend our mission, we took along some high-density food bars and every third day we supplemented our meals with these so we could extend our mission from 56 to 84 days. During those days, we had the same amount of minerals, the same number of calories as we would on other days, but the amount of food bulk was greatly reduced, so we ended up fairly hungry on every third day. We were glad to do this, but that was an effect. Second, we noticed, especially early in the mission, that we tended to get hungry in 3, 4, maybe 5 hours after a meal as opposed to

the normal 6 to 7 hours as one does down here. Whether that's an effect of zero gravity or whether that's an effect that we were just charging real hard the first couple of weeks, we can't sort out ourselves. But the effect was there.

Another effect of the food was from the Mineral Balance experiment M071. It was a very worthwhile experiment, but it certainly did have its impact on the food system. I think, in the future, once we've learned all we can from that experiment, we'd like to see a food system where one can choose what one wants to eat, when one wants it, and how one wants to prepare it; that is, how much salt or other seasoning one wants to use. To have a little more flexibility of choice, we're thinking of a pantry as opposed to the more or less rigid diet which we were on. Again, these comments are directed toward what we would consider optimum from the crew operational standpoint, and in no way do we mean that this was not a worthwhile experiment. We were glad to cooperate in it.

Exercise. As already has been mentioned, we exercised for one-and-a-half hours a day. I think we came back in as good a shape, maybe better, in some respects, than previous crews. We attribute that to two things, both of them based on the experience that we gained from the other flights. First of all, we exercised longer, an hour-and-a-half in our case; and second, we knew just what exercises we should do. For the arms, we used a Mark I exerciser, which is an inertial wheel resistance device; it worked real well. For the legs, we took along a new device which, for us, I think made a significant difference; this was the Thornton treadmill. Bill Thornton dreamed it up. We called it "Thornton's Revenge". It essentially is a very thin sheet of Teflon®, about a foot-and-a-half wide and maybe three feet long. We put it on the floor, got on it with our stocking feet and adjusted some bungee cords which went over the shoulders and held us down to the floor with essentially our own weight. In that way, we could walk, or run, or bounce up and down. This exercised the calves of the legs in a way which just couldn't be done on any of the other devices we had onboard. For us, it did make a significant difference. Also, for cardiovascular conditioning, we all worked out on the bicycle; we were glad we had that onboard. We always felt good after we used it. One thing about the use of the bicycle, and I don't mean to be facetious at all in pointing it out, is that when one is working for a long time on that bike, 15, 20, 30 minutes or so at fairly high workloads one needs something to divert his mind. I think that if we had a window right by the bicycle, it would have been good. What we used was a tape recorder and music. And I found with music I could go a heck of a lot longer and harder than without it. It may be a small point, but it sure changed the amount of exercise which we could consistantly do.

Scheduling. We've seen a progression during the manned space flight program from the early types of flights to the ones we had in Skylab. Mercury, Gemini, and Apollo were relatively short, high-effort, go-to-the-hilt-for-a-short-period-of-time-type missions. Plan everything down to the last detail; that's the best way to fly that type of mission. In the early Shuttle Program, we'll probably experience the same type of flights. Skylab, however, had very long missions. One had to become a jack-of-all-trades, and one had to use an awful lot of judgement in gathering the data in several types of experiments. That implies that in-flight one needs a certain time to organize, especially early in the mission. We all experienced this in Skylab 4, it's borne out by a paper which Owen Garriott will give tomorrow, and it's also borne out by the productivity of all three crews considering the various inputs. One needs a certain time to analyze one's situation and to develop new techniques, whether it be how to completely redo an experiment technique because it's just not working or whether it's just a way to hold a checklist. One certainly needs this extra time in order to get one's self efficient. Something like two to three hours per day would be useful to have as a time to get organized. Shopping list items could be used to fill the time left over. This is very much preferred to scheduling 16 hours a day to the hilt. What I'm saying is that the crew ought to be allowed to come up to their peak efficiency as opposed to working against a predicted efficiency. Giving them extra time to get to their peak efficiency will result in getting much more out of the total mission.

Training. Inflight Medical Support System. I was very enthused with this one and really enjoyed it. We, in our training, learned a little bit about extracting teeth, suturing, and blood drawing. I felt fairly comfortable with my ability to do any of the procedures in-flight had we needed any of them. We certainly did do a lot of blood drawing. Fortunately, we did not have to get into any of the other aspects: suturing, tooth extraction or diagnosis. We had a few small things that we had to diagnose but no major illness. We did have the capability of doing some microbiological examinations on board. I had worked quite heavily in that before we left and felt fairly confident. We did have some training from the NASA surgeons here and physicians in Houston, and they were always enthusiastic and exceptionally helpful. My only regret is that we didn't get involved in it earlier. We started it when we got pretty heavily involved in all of the other mission training phases.

Fluid shift. This is perhaps one of the larger points that we're still pondering, at least, in the crew's mind on this flight. We had early in the flight, what I'll describe as a general symptom called "head fullness". This is when the body fluids shift to the upper part of the body when one first enters into zero-g. One notices that the eyes turn

red which, in my case, happened after about a day or so. The eye sockets themselves become a little puffy; the face, a little rounder, a little redder; veins in the neck and forehead become distended and one's sinuses feel congested. And these conditions did not changes significantly in-flight; they just tapered off. The bloodshot eyes disappeared but the congested sinuses were always there, although it was more severe at the beginning. On our flight, the Pilot noticed this. Bill Pogue noticed this during the rendezvous; he had the headfullness during the docking, experienced some headache and some general malaise and felt pretty much like he had the flu, as he described it. In order to be a good buddy, we said, "Bill, why don't you have some food, it will make you feel better". He took some tomatoes and very shortly after that returned them to us. That was the only occasion we had on our flight of vomiting. After around 24 hours, Bill's headache disappeared. The congestion for all of us remained, although I think it was probably a little more severe for Bill. This feeling of head fullness and the accompanying symptoms, the Commander and I noticed for the first two weeks or so. If one asks one's self whether one still had them toward the end of the mission, one would have to say "yes" but they were really not too bothersome. The Pilot noticed that for the last two weeks of the mission he really felt good and essentially equivalent to 100 percent on the ground. He was working fairly close to that during most of the flight, but he remarked that the last two weeks of the flight he felt much better.

I noticed several variables that affected the fluid shift symptoms and our head fullness. One was exercise. We always felt a heck of a lot better after we exercised on the bicycle. Perhaps the effect of just drawing the blood down into the larger muscles of the body took it away from the head; it always cleared out the head, and we always felt much better for about a half hour to two hours afterwards. The Commander on our flight noticed that after eating he also experienced this to some degree. And also, the last effect was associated with the time of day. As down here, if one had anything bothering him, towards the end of the day it always feels worse. The same was true up there with the feeling of head fullness.

We were also able to see the leg volume changes because of the fluid shift. First of all, we could see them shrink when we got up there. You could tell it by eye, and you could tell it by measurements. A couple of times we measured the calf after exercise on the treadmill. It increased about a half an inch or so after a reasonable amount of exercise and, of course, it shrank down fairly rapidly as soon as we stopped.

Subjectively the distress was significantly higher in-flight when we used the Lower Body Negative Pressure Device, which we had onboard.

This was borne out by the results which you will hear later. About four to six weeks into the mission was worst for us, and that is consistent with the data. We used the symptoms of presyncope as a cutoff for the Lower Body Negative Pressure test. We monitored pulse pressure and heart rate, but primarily, we used the subjective symptoms of the individual. In some cases, the pulse pressure and heart rate would get into the same ranges as they had been on a previous day for that individual, but he might say: "No, that's it. I feel as though I'm going under and you better terminate now". Other times we could go right through the test without any problem. We really had to consider all the variables and the crew symptoms.

Vestibular effects. Preflight we flew T38 aerobatics primarily to reduce our sensitivity to motion sickness. We also did some work in a rotating chair with scopolamine/dexdroamphetamine (scop/dex). We never used scop/dex when flying a T38 because it gave us a feeling of being lightheaded and we did not want to be flying under those conditions. The preflight T38 flying, I thought was the most significant part of our vestibular-type training. We did aileron rolls while putting our heads in one of six different orientations. We did 15 to 25 rolls in a row while putting the head down, to one side, or back, or one of the three opposite directions. One could get a great stress on one's semicircular canals. We noticed very significant improvement in our ability to tolerate vestibular stress after we had made several flights.

Next let us consider the relationship between our vestibular stimuli and nausea. First, I'll make a comparison between myself and Bill Pogue. Bill did get sick early in the mission. If anybody should not have gotten sick, it was Bill. He had many years of flight experience and used to fly with the Thunderbirds. When he was first tested, he was able to go at 25 rpm in the rotating chair for 150 head motions. We called him "old lead ear". He had no problem whatsoever on the ground. On the other hand, I'm relatively new at the flying game. I had about 3000 hours of flying time before I went and was just normal in my tolerance in the chair. Maybe 12-1/2 rpm was what I could take initially, although I was able to work up to 30 before I went because of the T38 flying. Bill went up and, as I pointed out, after about seven or eight hours into the mission, got sick. Both of us did about the same moving about the command module, which was a very small amount. I experienced very minimal symptoms and never really anything in the way of discomfort at all. So, the conclusion here is that we've got to look for something else other than what normally we call "motion sickness" as a generator of nausea! We suggest fluid shift may be intricately tied up in this but I'll not try and second-guess all the physicians.

We never had stomach awareness when we were up there. We experienced a sensation of tumbling after we were in the rotating chair and during

acrobatics in the workshop. I used to do 15 or 20 forward rolls or gainers in a row and get really severe nystagmus although I never had any coupling to the stomach.

On return when we first experienced one-gravity during the first deorbit burn, after 84 days in weightlessness, we all noticed a rather strange sensation in the inner ear. It was like a tumbling sensation, similar to what one gets when lying on a table and someone puts cold or warm water in your ear. It had that aspect to it, but we did not feel that we were tumbling in a given direction. It was just an awareness of a sensory input that we had not experienced for a very long period of time. We'd had no real parallel to that one here on the ground. After recovery, we found rapid head movements produced vertigo. Most crews have noticed this. Also, the brain was not coupled to the muscles in the same way as they were before we left; that is, we all felt very heavy. Every movement we made had to be worked at. Rolling over in bed, moving an arm, walking; they all had to be conscious effort. And this lasted for a couple of days and was very much more severe at the beginning than at the end of those two days. We could go around corners fairly well, if we were careful. We tended to walk with our feet spread apart. I think that had we had any contingency on the return we would have been able to handle those which we had planned for, but certainly we were a bit less able to handle them than when we left. That's to be expected, and I still think we all felt fairly comfortable as we got out of the Command Module.

We all felt very thirsty on the recovery ship despite the fact that we had really forced the fluids before we returned. It was expected, of course.

The joints, especially the knees, felt sore after we exercised a little bit down here on the ground. My leg muscles were sore; for the Commander, it was his back.

One other interesting point in the vestibular area is our perception of orientation in flight. For example, being upside down in the wardroom made it look like a different room than what we were used to. When I started to rotate back and got to approximately 45 degrees or so of the attitude which we normally called "up", the attitude in which we had trained, there was a very sharp transition in my mind from a room which was sort of familiar to one which was intimately familiar. It all of a sudden was a room in which we felt very much at home and comfortable with. It wasn't a gradual thing; it was a very sharp transition. This phenomena we observed throughout the whole flight. I also noticed the feeling of "down". I experienced it a couple of times when I was working in the multiple docking adapter or the airlock. When moving around in those vehicles, I attached no direction to my motion at all. But

after I would look out the window for a long period of time, in particular the window for the Earth Resources Experiment Package, and then move away from the window and look from the multiple docking adapter to the airlock, I strongly felt that I was looking "down". In the back of my mind I said, "I'm going to fall if I don't hold on". Of course, I knew that it was not true, and just pressed right on. But that thought did flicker through my mind several times. The other "down" I noticed was a very exhilarating one, and that was outside during the extravehicular activities. When I went out to the end of the Apollo Telescope Mount, had my feet in the foot restraint and leaned back, I felt very far away from the space station. I no longer felt a part of it, and when I looked down, I suddenly realized that it really was a very long 270 miles down.

Miscellaneous items. I did notice a ballistocardiographic effect. That is, a couple of times when I was trying to take pictures out a window and just held on to the adjoining structure rather lightly, I noticed that the whole Skylab cluster was beating at around 60 beats per minute. This was evident several times. It required that I hold myself down rather firmly to get around this.

Many of us noticed, subjectively and without taking measurements, that the fingernails and toenails tended to grow a little bit slower inflight. Rather than trimming them once a week it was on the order of once a month or so.

We all experienced light flashes. We noticed on our flight that they were well correlated with the South Atlantic anomaly. After some major flares on the Sun during one night, we saw a high number of flashes. Most of them appeared as a white, double-elongated flash, perhaps double in some cases as other people have described, and Bill Pogue and I also saw the ones which looked like a whole multitude of pollywogs; very short ones, many of them of low intensity. For us, the latter kind occurred on the second orbit after we saw the very bright ones, suggesting they are of lower energy but of many more particles. Also, I saw one green flash. Not a slightly green flash but a good old St. Patrick's Day green flash, and exceptionally bright.

It was a surprise to us that we had no major illness, especially on our flight. We were working hard most all the time and got rather tired. We stayed tired for about the first half to two-thirds of the mission. If we had done that on the ground, I don't think we would have gotten by without getting at least a good cold. Up there, we did not have any major problems . I cannot speculate the reason for it.

We all found it was useful to sleep using the device that we had up there. It was a cot outfitted with four straps which held us down and made us feel as though we were sleeping in something similar to a bed. On several occasions, I tried sleeping by just floating free in the workshop. It was kind of fun, but I could only catnap that way. I floated pretty much with my arms out, like I would in a relaxed position underwater. You'll see some pictures later of just what our relaxed position was. I'd mash into a wall rather slowly and five minutes later come up against another one. My mind was always half awake, waiting for the next contact. I could never really get a sound sleep that way.

The duration of our mission was 84 days. We felt that we could have gone significantly longer than that. We're talking on the order of a year, from the crew standpoint. First, we felt good physically, especially the last month. We felt much better than we did at the beginning of the mission. And second, the types of tasks and the scheduling which are required must be carefully considered. Let the crew get ahead. Let them set their schedule and build up to their highest efficiency and maintain it that way. The types of tasks which are required, especially for long missions, are those which require judgment and those with which one can grow and get better at, those which, for example, one can do better on day 102 than one could on day two, those which really are challenging intellectually.

We have learned from Skylab that man makes his best contributions on tasks which use his intellect and require his judgement and that his proficiency on these types of tasks increases with mission duration. Thus, there should be very strong motivation for future long duration missions.

SKYLAB 2 CREW OBSERVATIONS AND SUMMARY

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JOHNSTON: Thank you, Ed. That was excellent. Our next speaker is going to give observations from Skylab 2 and kind of a summary of the crew. Joe Kerwin is our first U.S. astronaut physician in space. He, of course, was the Scientist Pilot in Skylab 2. He's currently head of our Life Sciences Astronaut Office. Joe.

KERWIN: Thank you, sir. It's a pleasure to be here at the Richard S. Johnston Space Center, as we call it in our office. Dr. Gibson, it's truly amazing to me how you could have stolen about half of what I was going to talk about, considering only the fact that we were in the same environment in the same vehicle for varying periods of time in the same year. It's really nice to get back and talk to the other crews and find out how consistent one's descriptions of the signs and symptoms of weightlessness are. It's the same environment, and it's just a matter of describing it in different words or different similes.

The diagnosis of weightlessness, by the way, is very simple. As in the case of many diseases, the history alone is often sufficient to establish the diagnosis. However, if you're in this situation and you are having some difficulty, I have devised a test - which with true humility, I recommend be called the Kerwin Test, for the presence of weightlessness. You have the patient place both hands on the examining table and push downward firmly; if he floats up toward the ceiling, the test is positive.

I have talked before about the signs and symptoms of weightlessness and there are two major themes that run through my mind. Number one, of course, is that it really is extremely clear to an individual when he is in weightlessness that rather profound changes are rapidly taking place in his body. One feels this strange fullness in the head and this sensation of having a cold and the nasal voice, and one sees the puffy look on the faces of his fellow crewmen. He feels this strange posture that one assumes in weightlessness, with the shoulders hunched up, and the hands are out in the front and the knees are bent.

It's not comfortable initially, sleeping in that posture, but every time one relaxes, one's body goes back to that posture. One can almost see the fluid draining out of the legs; one looks at his partners, and their legs are getting little and skinny like crows' legs, and one knows that one's physiology is changing. But that wasn't the primary theme. The primary theme was one of pleasant surprise at all the things that didn't change, at all the things that were pleasant and easy to do. As Pete Conrad pointed out, we lost a few bets up there because of our appetites. But the very first system that we had pleasant surprises in was the vestibular system. We all keep talking about it because not only was it so different from what was expected but it is, subjectively, one of the primary memories that one gets from this "Alice in Wonderland" world of weightlessness.

Our crew was fortunate enough not to run into the motion sickness problem in any clinical or full-blown form. Therefore, our first pleasant or different impressions were the impressions of a very changed relationship between ourselves and the outside world. And, in my own words, I would say that there was no vestibular sense of the upright whatsoever. I certainly had no idea of where the Earth was at any time unless I happened to be looking at it. I had no idea of the relationship between one compartment of the spacecraft and the other in terms of a feeling for up/down, and this has some peculiar effects when one passes from one compartment into the other and walls turn into ceilings and ceilings turn into floors in a very arbitrary way. But all one has to do is rotate one's body to the comfortable orientation and whamo! What one thinks is up, is up. After a few days of getting used to this, one plays with it all the time; one just stands there and does a slow roll around his bellybutton. It's a feeling as though one could take this whole room and by pushing a button, just rotate it around so that the screens up here would be the floor. It's a marvelous feeling of power over space - over the space around one. Closing one's eyes, of course, made everything go away. And now one's body is like a planet all to itself, and one really doesn't know where the outside world is. The first time I tried it, my instinct was to grab hold of whatever was nearest and just hang on, lest I fall. It was the only time in the mission when I had anything like a sensation of falling. I was telling that to my wife, and she pointed out that that's like the reflex that a baby has. When you begin to drop it, it just reaches out and clutches. And we thought, wouldn't it be nice to write a story about a sort of re-evolution of the human being in zero-g, because one certainly gets used to it in a hurry and it certainly is different. You will hear in great detail later on in the symposium about the third and last effect of weightlessness on the vestibular system, again alluded to by Ed, that rotation and head movement in weightlessness do not elicit motion sickness. I don't believe Dr. Graybiel will state it quite that strongly, but certainly we never reached the threshold. And that was most surprising.

Another very pleasant surprise was our ability to maintain physical fitness - our ability to maintain an exercise level the same as we had been maintaining on the ground. I really don't think that any of us expected that before the flight. One was moving around in a large volume. One was maintaining weight in the face of what we knew was going to be a markedly reduced caloric intake. We just knew it; never mind that it was wrong. And the third was that we felt that a combination of mechanical efficiency and muscular deterioration or atrophy was definitely going to reduce our ability to work on the bicycle. Well, we were wrong again. Once we had mastered the technique or the mechanics of how to ride a bicycle in a weightless condition, which took us about 10 days, we found that essentially we remained at the preflight baseline through the mission. I believe some of the crewmen on the subsequent flights increased their ability to do that particular task, simply through a training effect, and that was a very pleasant surprise.

To me, the most astonishing thing was our ability and desire to pack in the groceries, and there's a long preflight history to that. We fought and scratched with the Principal Investigators on that diet for four or five years. We finally settled on an in-flight diet estimation, which kind of went like this: We had several six-day periods of food intake measurement prior to the flight. These data were taken and were modified by certain standard height/weight/surface area tables, and so forth, to get a best estimate of our average caloric intake, and then we subtracted 300 calories from that. Most of us were certain that even that amount of food was going to be too great. And lo and behold! Didn't we discover that after a few days of decreased appetite in flight, we found that on most days we were able to eat all of our food. As Pete even pointed out, man does not live by bread alone, but by butter cookies and ice cream. Indeed, as the missions progressed and the amount of food the crew was allowed to eat increased and their exercise increased, they were essentially eating the same amount of food that they ate on the ground. That to me is a mystery. I still don't understand it but maybe I will by the end of the symposium. How in an environment in which certainly muscular work is reduced, the caloric demand and the relationship between caloric intake and body weight remain just about the same as they do on the ground, I think that's a very interesting problem that we haven't solved yet.

Okay, we described a number of other phenomena on our flight, many of which Ed had already covered in terms of signs and symptoms, in terms of physical findings on physical examination, in terms of simple laboratory work - which go toward a beginning of putting together a rational description of the physiology of weightlessness. The first step is a medical history and physical examination. This we follow with laboratory findings and the clinical course of the - I hate to call it a disease because it's not - but, of this change. Such a description

has many uses, not the least of which will be to permit the diagnosis of disease in weightlessness, where the presenting signs, symptoms and so-called normal laboratory values are going to be different. Now our sample population has been much too small to have experienced significant illness in orbit, and it's been too small to allow us to predict changes in the incidence of diseases or the course of diseases due to the weightless environment. I think this is a matter of time and that these are the kind of things we need to know in order to fly frequently and to fly for long durations and to make space flight in the Shuttle era, and beyond, a routine event, because we do not want to limit our crews and our visiting scientists to people who are completely free from disease or from unusual tendencies. There are a million examples come to mind: for instance, when you fly older people, what is the rate at which they wash out nitrogen when they prebreath? Does it change merely as a function of age, or is it because physical fitness and obesity come into the picture, too? We don't know. That's a small data point that's going to be operationally important to us when we begin to fly people in their 50's and their 60's. I think the first step is to use animal subjects to make the invasive measurements necessary to clear up the picture, and to observe the response of animals to various challenges that are difficult or dangerous to do on human subjects, such as radiation, hypoxia, and acute blood loss. I think the effect of hypoxia in weightlessness would be very interesting to observe. Certainly, I'd love to see whole generations of animals reared and exposed to weightlessness for their entire lifespan, to see how far this evolutionary process will really go. And I think eventually we will get to the point where we will dare to study disease states, first in animals and then in human beings. I think that by studying a disease in weightlessness, we will learn more about both the environment and the disease. There are, as I said, many possibilities: from fundamental studies on coronary and pulmonary perfusions, to bone and soft tissue healing, to the effect of drugs in hypoxia and radiation, to observations on the course of stasis ulcers and to how does edema in right heart failure behave in this environment. If we can make fundamental advances in any one of those subjects, we'll pay the freight for the whole medical program. I am not suggesting a shotgun approach but I feel that an imaginative approach to medical research will have an opportunity to be used in the 80's.

I would like to conclude with a few observations by one such human subject on a space flight. We had a super relationship with the medical team on Skylab. Each and every investigator was competent, efficient, and thoughtful of us, the subjects. Only *en masse*, were they ever the tiniest bit overwhelming, as when on recovery day everybody wanted that significant data - "right now". I think we struck a good balance, and I hope we continue to do so. Medical research on Skylab has helped us

to document that human beings can operate efficiently in space. It's this fact, rather than medical research *per se* that will justify continuation of manned space programs. It appears that man's potential efficiency in zero-g is as high as it is any place else. The degree to which this potential is realized is a function of the experience and training of the crew and of the degree to which their needs are met in flight. Thus, the function of medicine is not only to discover those needs but to meet them. And the research program we design must hamper the crew's efficiency as little as it's possible to do and still get the data. And so to all you good research people, one final admonition: You can have all of the data some of the time, and you can have some of the data all of the time; but you can't have all of the data all of the time. Thank you.

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SKYLAB CREW HEALTH - CREW SURGEONS' REPORTS

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ABSTRACT

A physician was designated as the Crew Surgeon for each of the three manned Skylab missions. He was responsible for the health of the Skylab crewmembers and their families, the development and use of the Inflight Medical Support System, the preflight medical examination and arrangement of all crew medical-related activities, and the postflight coordination of medical activity on board the recovery ship and afterwards at the NASA-Lyndon B. Johnson Space Center.

Skylab 2, lasting 28 days, was the first manned Skylab mission. The only Skylab 2 preflight problem was gastroenteritis in one crewmember one month before flight. During the entire flight, the Commander had a left serous otitis media. Postflight adjustment was clinically satisfactory, but the Pilot was presyncopal after completion of the Metabolic Activity experiment M171 exercise protocol on recovery day, and the Scientist Pilot experienced significant seasickness on that same day.

Skylab 3, a 59-day mission, was the second manned Skylab flight. The Skylab 3 preflight period was free of medical problems. During flight, all three crewmen experienced motion-sickness during the first three days. A sty and two axillary boils developed on the Commander during flight, but resolved without complication. On recovery day, the Pilot developed presyncope in the recovery phase of the experiment M171 exercise protocol, and the Commander was presyncopal during the stand test. In addition, the Commander aggravated a back problem which he had had preflight. Postflight, the overall clinical adjustment was more rapid than for the Skylab 2 mission crewmen.

Skylab 4 was the longest and last manned Skylab mission; it lasted 84 days. No acute medical problems occurred before the Skylab 4 flight. The Scientist Pilot's left eardrum was variably injected, but followup care through the preflight period allowed flight clearance. During flight, two of the three crewmen experienced motion-sickness symptoms during the first three days. Skin dryness and head and nasal fullness were present as in the earlier two missions. The Pilot

had a probable fungal infection which cleared after two weeks of therapy. Sleeping medications were used more throughout the Skylab 4 mission than in the Skylab 2 or Skylab 3 missions. Food intake was satisfactory, and less weight was lost by the crewmen than on the two previous missions. Exercise time was longer than on previous missions. A unique treadmill was used for the first time. The expertise in handling flight planning problems associated with long-duration missions was significantly developed during this 84-day flight. On recovery day, the Commander experienced presyncope following a forced expiration test maneuver. Overall postflight crew readaptation was clinically very good and was even more rapid than for the two preceding flight crews.

INTRODUCTION

Prior to the flights of the various Skylab missions, the Crew Surgeons had responsibility for the following medical areas.

- To supervise the health of the Skylab crewmembers and their families.
- To render clinical assistance in the development of the Inflight Medical Support System (IMSS) Checklist and equipment, as well as to monitor the Crew IMSS training programs at the various professional sites.
- To conduct IMSS drug sensitivity testing (topical and oral), and electrocardiographic, vectorcardiographic and electroencephalographic skin sensor sensitivity testing.
- To monitor medical experiment baseline data.

During the preflight, in-flight and postflight periods, the Crew Surgeons gave careful surveillance to the following areas of medical concern:

- illness events and prescribing medications,
- trends in the Flight Crew Health Stabilization Program,
- nutrition, intake and output,

- personal daily exercise,
- work/rest schedules, and
- sleep periods, quantity/quality.

The Crew Surgeons relied to a great extent on the daily private medical conference with the crews over an air-to-ground loop from the NASA Mission Control Center to monitor crew health in-flight. For continuous clinical evaluation of the crew, the Crew Surgeon had access to medical parameters derived from the experiment data and was also dependent on the following monitored areas for clinically related information:

- radiological health,
- Skylab environmental data, including toxicological evaluation, and
- medical data obtained from the Operational Bioinstrumentation System during the scheduled extravehicular activities.

Postflight, the Crew Surgeon coordinated all the medical activities relating directly to the crew. He was the medical team leader on the recovery ship and had prime responsibility for the continuous clinical care of the crew especially during the medical experiments, and later at NASA-Johnson Space Center.

SKYLAB 2

Medical examinations performed on the three crewmen at specified intervals beginning 40 days preflight did not reveal any major change in any crewmember's health status. They remained in good health throughout the preflight phase, except for the Pilot who developed a 24-hour illness resembling a viral gastroenteritis about one month before flight, just coincident with the initiation of the Flight Crew Health Stabilization Program.

In-flight, on mission day 1, the Commander developed a left serous otitis media, which required the extended use of an oral decongestant as well as a topical nasal decongestant. On mission days 3 through 7, the Commander also used a topical steroid cream to relieve the symptoms of a probable mild contact dermatitis of his right arm. Complying with a preflight decision, the Scientist Pilot took one scopolamine/dextroamphetamine sulfate capsule just after insertion, but the medication was not repeated. Prior to extravehicular activity, the Scientist

Pilot and the Pilot utilized a topical nasal decongestant prophylactically; the Pilot also took an oral decongestant.

No significant arrhythmias developed in-flight. Early terminations of the Lower Body Negative Pressure experiment (M092) by the Scientist Pilot and Pilot were sporadic, and in this mission the maximum level of exposure to lower body negative pressure was reduced following early termination of the Lower Body Negative Pressure test.

The crewmen took hyponotic medications of choice on the night of mission day 27 to help accommodate a change to their work/rest schedule for entry and splashdown. Entry itself was nominal. Postsplash (on the water) the heart rates were: Commander, 84; Scientist Pilot, 84; and Pilot, 76 beats per minute. Aboard the ship on recovery day vertigo, postural instability (especially with eyes closed), reflex hyperactivity, and paresthesias of the lower extremeties were prominent findings. The Scientist Pilot developed seasickness while still in the Command Module and the most prominent symptoms cleared in four to six hours. Scaling of the skin of the hands was noted on the Commander and the Scientist Pilot. The Pilot experienced a vagal response (decreasing heart rate, pale and sweaty appearance) in the recovery period of the Metabolic Acitivty experiment (M171), which lasted just a few minutes. Muscle and joint soreness, generally confined to the lower back and lower extremities, were first noted on the first day post recovery. During the ongoing postflight period of surveillance, no significant medical problems developed as an apparent result of the long duration in weightless space flight. No drugs were taken except for vitamins.

SKYLAB 3

Preflight, no infectious diseases or other medical problems were experienced by the crew during the 30-day preflight period, the last 21 days of which included the Flight Crew Health Stabilization Program.

Launch and orbital insertion were nominal. Shortly after orbital insertion, the Pilot began to experience nausea; this was aggravated by head movement. One hour after insertion, the Pilot took an anti-motion sickness capsule, scopolamine/dextroamphetamine sulfate, with good relief. The crew entered the Orbital Workshop 9 hours and 45 minutes after lift-off. Following strenuous work to activate the Orbital Workshop, the Pilot vomited once. During the second mission day, the Commander and Scientist Pilot also experienced some motion sickness during continued Orbital Workshop activation; they took scopolamine/dextroamphetamine sulfate as required for alleviation of symptoms. This

indisposition caused a loss of work time during the first three days of flight. Two additional days elapsed before all symptoms had dissipated. Since medical experiments were not run until mission day 5, subjective voice reports by the crew were the only means of health assessment during this time. On mission day 5, after the first medical experiments were conducted, objective clinical data were available to aid in evaluating the crew's health. In general, the crewmembers remained in excellent health except for a few minor clinical problems and rare sporadic early terminations of the Lower Body Negative Pressure experiment by the Commander and the Scientist Pilot.

The Pilot reported a painless sty on the left upper eyelid on mission day 29, which responded to an ophthalmic antibiotic ointment and cleared by mission day 32. On mission day 33, the Commander reported the beginning of a boil under his right arm. Instructions from the ground to the Commander were to avoid using stick-type deodorant, and the wearing of garments which fitted tightly under the arms. No medications were recommended and the condition cleared in about 48 hours. A recurrence of the boil in approximately the same area on mission day 50 again lasted only 48 hours, and did not require any medication.

The crew maintained high levels of daily exercise during the mission. Extravehicular activities were successfully completed on mission days 10, 28, and 57 without medical problems.

The crew slept 6 hours on the night prior to entry and were awake approximately 15 hours prior to splashdown. The Scientist Pilot took an antimotion sickness capsule approximately 40 minutes prior to the entry burn, while the Commander and the Pilot took their antimotion sickness medication approximately 5 to 10 minues after the burn. Prior to the burn, all three crewmen inflated their orthostatic counter measure garments. The entry was nominal. At about 20 to 30 minutes after splashdown while still in the Command Module, the Scientist Pilot checked the pulse rate of each crewman and obtained the following values: Commander, 88; Scientist Pilot, 70; and Pilot 62 beats per minute. Pulse checks by the Crew Surgeon immediately after the Command Module was aboard the recovery ship were similar. Blood pressures were within acceptable ranges for these crewmen. All three crewmen egressed the Command Module on their own power.

Postflight the cardiovascular deconditioning observed was carefully documented, but no clinically serious events occurred. As in Skylab 2, vertigo, postural instability, hyperreflexia, dry skin and slight fissuring of the hands were noted. On recovery, a previous back strain suffered by the Commander recurred from a situation combining "lifting" and loss of balance. On recovery day the Commander developed

presyncope during the stand test. The Pilot had a vagal response, also associated with presyncope, during the recovery phase of the Metabolic Activity experiment M171 (bicycle ergometer). The overall rate of recovery postflight was more rapid than that observed in the first manned Skylab mission.

SKYLAB 4

In Skylab 4, the Flight Crew Health Stabilization Program lasted 27 days due to a 6-day slip in the launch for evaluating and correcting potential launch vehicle problems. The crew underwent preflight evaluations, which were augmented by several new experiments, such as echocardiography and pulmonary function evaluation. Several items noted in the medical history and clinical examinations required attention for the upcoming flight, these were: a history of low back pain (lumbosacral strain) experienced by the Commander in the preflight period, and the concern as to whether there would be recurrence of this pain on his return to earth; some recurring variable left ear drum injection and lability of blood pressure noted during the preflight period in the Scientist Pilot; and the history of recurrent nasal congestion and a tendency toward lability of blood pressure in the Pilot. Cardiovascular review of these men showed no evidence of nor tendencies toward arrhythmias. These findings were well documented in order to permit evaluation of any in-flight changes. The crew remained in good health throughout the preflight period.

This crew also had no formal scheduled in-flight medical examinations. Data from experiments and "as necessary" medical evaluations continued to provide the necessary information for monitoring of health status. A heart rate and blood pressure stress evaluation for clinical reasons would be obtained on any individual at least every four days, if for some reason the experiments Lower Body Negative Pressure (M092), Vectorcardiogram (M093), and Metabolic Activity (M171) were not able to be run. Fewer illnesses occurred in-flight than would have been predicted from ground based experience. However, it is important to point out that in this mission there were numerous symptomatic events that required variable amounts of medication. Drug utilization for the three manned Skylab missions are delineated in appendix A. For all Skylab 4 crewmen, the initial medication was the prescribed antimotion sickness drugs. In Skylab 4 the Scientist Pilot did not experience motion sickness. The Commander had minimal malaise for three days. The Pilot had significant nausea with vomiting for one day and then malaise for two more days. The second major recurrent use of medication was lip balm and skin cream to prevent drying of the lips and skin, respectively. The sleep medications were utilized intermittently throughout the mission by all the crewmen. Decongestants (topical

and systemic) were used during the mission. These were used both prophylactically during the extravehicular activities and for specific symptomatic relief of the feeling of fullness in the head, nose and ears.

The Scientist Pilot utilized aspirin twice for transient headaches on mission days 17 and 67. On mission days 75 through 79, the Scientist Pilot utilized wet packs to help resolve a minimal papular rash on the left neck and ear area.

The Pilot had a rash in the upper mid-back area, which was treated as a fungal infection, and which did resolve after about a week and a half.

The observed in-flight problems were not related to preflight problems except remotely; one could state that the Pilot's prior history might have indicated the greater susceptibility to upper respirator congestion.

In following the crew, the Daily Health Status Summary sheet was a comprehensive guide. It was updated for this particular mission, and it was maintained by the person in the aeromed duty position working in direct support of the Mission Operation Control Room Surgeon. Data for this summary were prepared from the Evening Status Report which gave sleep, medication, exercise, and experiments M071 (Mineral Balance), M073 (Bioassay of Body Fluids), and M172 (Body Mass Measurement) data, from the dump tapes, and from the private medical conference. The latter permitted subjective and objective crew observations about their responses to the stressor tests (Lower Body Negative Pressure and Metabolic Activity) as well as to the general status of living in zero-g.

Vectorcardiographic data became especially valuable as the Pilot began demonstrating vectorcardiographic parameters differing significantly from preflight. None of these deviations from preflight "norms" were considered clinically abnormal. In a summary statement, there were neither clinically significant cardiac arrhythmias nor vectorcardiographic changes in-flight.

Instrumental in maintaining crew health was a maintenance of a proper environment. It should be stressed, there were no significant problems in maintaining the limits of environmental conditons of total pressure, oxygen, and carbon dioxide. Other parameters, such as temperature and relative humidity, were more variable. These parameters were influenced by the orbital inclination and sun angle of the Skylab complex and the performance of the supplementary thermal protection devices; additionally, potential off-gassing from the heated spacecraft was satisfactorily circumvented.

Personal cleanliness was fairly well maintained but proved to be time consuming, either by use of the shower or by sponge baths.

The increased quantity and quality of exercise available to the crew was important in maintaining crew health of Skylab 4. For each successive mission the exercise time had been increased from one-half hour, to one hour, to one and a half hours per day, respectively. In Skylab 4 the bicycle ergometer, the Mark I (an isokinetic force generating pulley), the Mark II (springs), the Mark III (the standard Apollo exercise device), the treadmill, and isometric exercises were available to counteract the effect of the zero-g environment; the crew had the highest overall average of quantifiable work output from their exercise.

The maintenance of nutrition was satisfactory; the Skylab 4 crew ate at essentially preflight caloric levels and were quite satisfied with the taste of the food. The high density food bars, utilized to extend provisions when the Skylab 4 mission was extended to 84 days, were tolerated well by the crew although they left a subjective sense of hunger. As in Skylab 3, vitamin supplementation was maintained. The weight losses for the Skylab 4 crewmen were less than those for the crewmen of the other two missions.

The work/rest cycle was a key problem in this last mission. During the early phase of this mission the crew was scheduled at a pace comparable to the pace attained by Skylab 3 crewmen in the latter part of their mission. New experiments, stowage confusion, onboard equipment malfunctions, and the sheer length of the mission were all contributing factors to produce psychological stresses which were slowly resolved over the first half of the mission.

As the end of the mission approached, two late single-block shifts of sleep time were made, as the preferred mode, to adjust the crew to the circadian shift required. Crew comments postflight indicated this was a suitable and effective approach to the time shift required. Earlier piecemeal shifting in Skylab 2 and Skylab 3 was not subjectively as effective. In preparation for entry, scopolamine/dextroamphetamine sulfate was prescribed for all three crewmen at approximately two hours prior to intended splashdown. The crew inflated their counter measure garments prior to burn and re-inflated them to compensate for the increasing internal pressure as the Command Module was pressurized during descent. As in Skylab 3, the splashdown was initially in stable-2 (heat shield up), and changed to stable-1 (heat shield down) within a nominal time frame. Initial "on water" pulse rates were: Commander, 70; Scientist Pilot, 80; and Pilot, 80 beats per minute. Blood pressure and pulse readings taken inside the spacecraft were acceptable and the crew egressed and walked essentially unassisted.

The triad of vertigo, postural instability and reflex hyperactivity was again noted postflight. This time it was the Commander who experienced a vagal response with presyncope at the end of forced expiration in pulmonary function testing. Petechiae were noted in the lower legs of all three crewmembers late on recovery day, and during the day afterwards. Muscle and joint soreness during exercise developed postflight, but only to a minimal degree. The postflight period was free of any illnesses or injuries. Postflight physiological readaptation, as measured by the experiements, revealed the crew to be in as good or better status than the crews of the two earlier missions.

CONCLUSIONS

From a clinical point of view, all of the physiological and psychological responses noted in the Skylab missions were either self-limiting or represented work-around problems requiring minimal counteraction. As such, these changes do not preclude extending man's duration in zero-gravity for longer periods of time.

Commander Drug Usage (Skylab 2)

MISSION DAY 1 AFRIN	2 DALMANE (1) AFRIN (1) ACTIFED (2)	3 AFRIN ACTIFED (2)	4 ACTIFED (1)	5	6	7
8	9	10 ACTIFED (2)	11 ACTIFED (2)	12 ACTIFED (2)	13 ACTIFED (2)	14 AFRIN
15 ACTIFED (2)	16 ACTIFED (2)	17 ASPIRIN (2) ACTIFED (2)	18 SUDAFED (2)	19 SUDAFED (2)	20	21 SUDAFED (2)
22 SUDAFED (2)	23 SUDAFED (2)	24 SUDAFED (2)	25 SUDAFED (2)	26 AFRIN SUDAFED (1)	27 DALMANE (1)	28

Scientist Pilot Drug Usage (Skylab 2)

MISSION DAY 1 SCOP/DEX (1)	2	3	4	5	6	7
8	9	10	11	12	13	14 AFRIN
15	16	17	18	19	20	21
22	23	24	25	26	27	28

Pilot Drug Usage (Skylab 2)

MISSION DAY 1 AFRIN	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24 SUDAFED (2)	25 SUDAFED (1)	26 AFRIN	27 DALMANE (1)	28

Commander Drug Usage (Skylab 3)

MISSION DAY 1 ASPIRIN (2) SECONAL (1)	2 SCOP/DEX (2)	3	4 SECONAL (1) NASAL EMOLLIENT	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
50	51	52 SECONAL (1)	53	54 SECONAL (1)	55 SECONAL (1)	56 SECONAL (1)
57	58	59 SECONAL (1)	60 SECONAL (1) SCOP/DEX (1)			

Scientist Pilot Drug Usage (Skylab 3)

MISSION DAY 1	2 SCOP/DEX (2)	3 MYLANTA (1) SCOP/DEX (2)	4 NASAL EMOLLIENT	5	6	7
8	9	10	11	12	13	14
15 AFRIN	16 AFRIN	17	18	19	20	21
22	23	24	25	26	27	28
50	51	52	53	54 SECONAL (1)	55	56
57	58	59	60 SCOP/DEX (1)			

Pilot Drug Usage (Skylab 3)

MISSION DAY 1 SCOP/DEX (1) SECONAL (1)	2 SCOP/DEX (2)	3 SCOP/DEX (3)	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
50	51	52	53	54 CHLORAL HYDRATE (1)	55	56
57	58	59	60 CHLORAL HYDRATE (1) SCOP/DEX (1)			

Commander Drug Usage (Skylab 4)

MISSION DAY 1 SCOP/DEX (1) PRO/EPH (1)	2 SCOP/DEX (2) PRO/EPH (1)	3 SCOP/DEX (2) PRO/EPH (1)	4 SCOP/DEX (1)	5	6	7	8	9
10	11	12	13	14 LIP BALM	15	16	17	18
19	20	21	22	23	24	25	26	27
28	29	30	31	32	33	34	35	36
37	38	39 CHLORAL HYDRATE (1)	40 SUDAFED (1)	41	42	43	44	45
46	47	48	49 SUDAFED (1)	50	51	52	53	54 SUDAFED (1)
55	56	57	58	59	60	61	62	63
64	65 SUDAFED (1)	66	67	68	69	70	71	72
73	74	75	76	77 SUDAFED (1)	78	79 SUDAFED (3)	80 SUDAFED (2) AFRIN	81 SUDAFED (1)
82	83 CHLORAL HYDRATE	84 CHLORAL HYDRATE	85 AFRIN SCOP/DEX (1)					

Scientist Pilot Drug Usage (Skylab 4)

MISSION DAY 1 SCOP/DEX (1) PRO/EPH (1)	2 SCOP/DEX (2) PRO/EPH (1)	3 SCOP/DEX (2) PRO/EPH (1)	4 SCOP/DEX (1)	5	6	7	8 PRO/EPH (1)	9
10	11	12	13	14 LIP BALM	15	16	17 ASPIRIN (2)	18
19	20	21	22	23	24	25	26	27
28	29	30	31	32	33 PRO/EPH (1)	34	35	36
37 DALMANE (1)	38	39	40	41	42	43	44	45
46	47	48	49 DALMANE (1)	50	51	52	53	54
55	56	57	58	59 DALMANE (1)	60 SUDAFED (1)	61	62 AFRIN	63 DALMANE (1)
64	65	66	67 ASPIRIN (2)	68	69	70	71 DALMANE (1)	72
73	74 AFRIN	75 AFRIN DALMANE (1)	76	77	78	79	80 AFRIN	81
82 PRO/EPH (1)	83 DALMANE (1)	84 DALMANE (1)	85 AFRIN SCOP/DEX (1)					

Pilot Drug Usage (Skylab 4)

MISSION DAY 1 PRO/EPH (3)	2 PRO/EPH (2)	3 PRO/EPH (2) SUDAFED (1)	4 PRO/EPH (2)	5	6	7 ORNADE (1)	8	9
10	11	12	13	14 LIP BALM	15	16	17	18
19	20	21	22	23	24	25	26	27
28	29 AFRIN (1)	30 AFRIN (3)	31 AFRIN (2)	32 AFRIN (3) TINACTIN (1)	33 TINACTIN (2)	34 TINACTIN (2)	35 TINACTIN (2)	36 TINACTIN (2) CHLORAL HYDRATE (1)
37 TINACTIN (2)	38 TINACTIN (2)	39 TINACTIN (2)	40 TINACTIN (2) AFRIN (2)	41 TINACTIN (2)	42 TINACTIN (2)	43 TINACTIN (2)	44 TINACTIN (2) AFRIN (1)	45 TINACTIN (2)
46	47	48	49 CHLORAL HYDRATE (1)	50 SECONAL (1)	51 SECONAL (1)	52	53	54
55 AFRIN (1)	56	57	58	59	60 SECONAL (1)	61 AFRIN (2)	62 AFRIN (1)	63
64	65 SUDAFED (1) AFRIN (1)	66 SUDAFED (1) AFRIN (2)	67 AFRIN (1)	68 AFRIN (2)	69 AFRIN (2) ACTIFED (1)	70 AFRIN (1) ACTIFED (1)	71 ACTIFED (1)	72 ACTIFED (3)
73 ACTIFED (3)	74 ACTIFED (3)	75 ACTIFED (3)	76 ACTIFED (1)	77 ACTIFED (2)	78 ACTIFED (1)	79 ACTIFED (1)	80 ACTIFED (1)	81
82 SECONAL (1) ACTIFED (1)	83 SECONAL (1)	84 SECONAL (1)	85 SCOP/DEX (1)	NOTE: QUANTITIES FOLLOWING AFRIN AND TINACTIN INDICATE APPLICATIONS				

DETAILED TEST OBJECTIVES

SKYLAB ORAL HEALTH STUDIES

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ABSTRACT

Oral health considerations for the Skylab series of manned space flights included three areas of responsibility: clinical, provisions for in-flight care, and research.

Clinically, prevention of dental disease was emphasized through frequent oral evaluations and an intensive home care program.

During all missions provision was made for an extension of the crewmen's home care program and equipment and training were provided all astronauts for self-treatment in-flight should the need arise.

Research was dedicated to the identification of potential oral health problems which might occur in prolonged space flights. Skylab crewmembers were monitored for: shifts in oral microbial propulations, changes in the secretion of specific salivary components, and alterations in clinical indices of oral health and preexisting dental disease.

Microbiological assessments were made weekly to biweekly from three intraoral sites (gingival sulcus fluid, dental plaque, and stimulated whole saliva) beginning as early as 57 days preflight and ending 17 to 20 days postflight. Preflight specimens were scheduled to provide comparison of microbial counts before and after the incorporation of space diets. In addition to microbial assessments, stimulated whole saliva was used to determine saliva flow rates and salivary protein,

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lysozyme, and IgA levels. Oral clinical evaluations were performed at 30 and 4 days preflight, and 4 days postflight for Skylab 2; at 43 and 5 days preflight and 4 days postflight for Skylab 3; and at 47 and 4 days preflight, and 4 days postflight for Skylab 4 to compare incremental changes in the accumulation of dental plaque, calculus formation, gingival inflammatory responses, and alterations in teeth, bone, and oral mucosa. The following were the most distinctive intraoral changes noted.

- Increased counts of specific anaerobic and streptococcal populations endogenous to the intraoral sites tested.
- Elevations in levels of secretory IgA's and saliva flow rates with diminutions of salivary protein and lysozyme.
- Increased increments of dental calculus and gingival inflammation.

Most microbiological changes occured in both the prime and backup crews of each mission, and appeared to be diet-related. Secretory IgA elevations occurred in the prime crews of each mission and were presumably due to subclinical infection. Explanations for increased saliva flow rates and decreased levels of salivary protein and lysozyme, which were not observed in all missions, were not readily apparent. Similarly, increased increments of dental calculus and gingival inflammation appeared to be individual rather than group related. Assuming no future clinical detection of mission-related intraoral complications, the most significant finding from these investigations was the relatively nonexistence of health-hazardous intraoral changes.

INTRODUCTION

Oral health considerations for the Skylab series of manned space flights included three general areas of responsibility. These areas were:

- clinical dentistry,
- provisions for in-flight care and the Inflight Medical Support System-Dental, and
- research dedicated to the identification of potential oral problems in manned space missions of long duration.

CLINICAL DENTISTRY

Clinically, the emphasis in the dental health program was on the prevention of dental disease. This was accomplished by a carefully supervised home care program which was supplemented with oral examinations and evaluations at least every six months. Regular topical applications of stannous fluoride were also provided all crewmen. However, because of consideration of other studies during the Skylab missions, the topical fluoride applications were discontinued six months preflight for each crew.

Because of risks of inflammation to the dental pulp, no dental restorations were provided the crewmen during the last ninety days prior to flight. The oral health of all crewmen was at a sufficiently high level that the ninety-day provision was realistic.

Complete oral Panorex radiographs were made of each crewman prior to his mission. These radiographs did reveal two asymtomatic, previously unrecognized areas of pathosis about the apex of the teeth of two crewmen. Both problems were successfully resolved.

During the last nine months prior to the Skylab missions, six crewmen required treatment for dental problems which were other than routine replacement of restorations and dental prophylaxes. These ranged from a large, symptomatic, recurrent aphthous ulcer, to significant inflammation and discomfort from local gingival inflammation, to a periapical abcess. All were resolved successfully with no recurrence.

IN-FLIGHT CARE

The possibility for an unanticipated dental problem occurring inflight which could significantly impair a crewman's ability to work effectively was computed at 0.92 percent for a 3-man 28-day mission. This figure was based on studies of dental experiences in other isolated environments, *i.e.,* polar expeditions, United States Navy FBM submarine patrols, and from a three-year study of the astronaut population. The most likely problems which could impair a crewman's effectiveness in-flight were judged to be either a painful tooth due to pulpitis or severe, localized gingival inflammation with or without a peridontal abcess. The pulpitis would be most likely to occur in a tooth which had previously been restored with a deep restoration which suddenly becomes symptomatic. This is a common ground-based dental

problem and the resulting potentially debilitating pain could occur for a number of reasons, including decreased resistance of the host and/or increased virulence of the organisms involved. Dental caries was not considered as a problem in missions of up to three months' duration because of the high level of oral health of all crewmen and the frequent dental evaluations they received.

Because of the risks involved, it was decided that a means be developed for treating the most likely dental problems that might arise. To this end the prime and backup crews of all Skylab missions received two days of intensive training in pertinent dental procedures at Lackland Air Force Base, Texas. The training included lectures, demonstrations, and supervised clinical procedures. The supervised clinical procedures performed on volunteer patients included complex procedures such as tooth removal. Instruments and medications were provided as the Inflight Medical Support System-Dental. As aids, this Inflight Medical Support System-Dental included a manual with line drawings of complete intraoral radiographs of each crewman as well as integrated, illustrated, diagnostic, and treatment procedures. Examples of these aids are illustrated in figures 1a, 1b, and 1c. Other aids included air-to-ground communication with a dentist and/or surgeon who had as aids intraoral photographs and radiographs, diagnostic casts, complete treatment records with narrative summaries, and complete knowledge of the treatment capabilities of each crewman as he was observed during the training program. No dental problems occurred during the Skylab series of missions which required use of the Inflight Medical Support System-Dental.

ORAL RESEARCH

Introduction

Skylab crewmembers were monitored to assess the effects of their missions on:

- ° the population dynamics of the oral microflora,
- ° the secretion of specific salivary components, and
- ° clinical changes in oral health.

Not only is oral health important to personal performance during prolonged space missions, but the oral region serves as a portal of entry for pathogenic agents, acts as a reservoir for infectious microorganisms, and plays a role in cross-contamination and disease transmission.

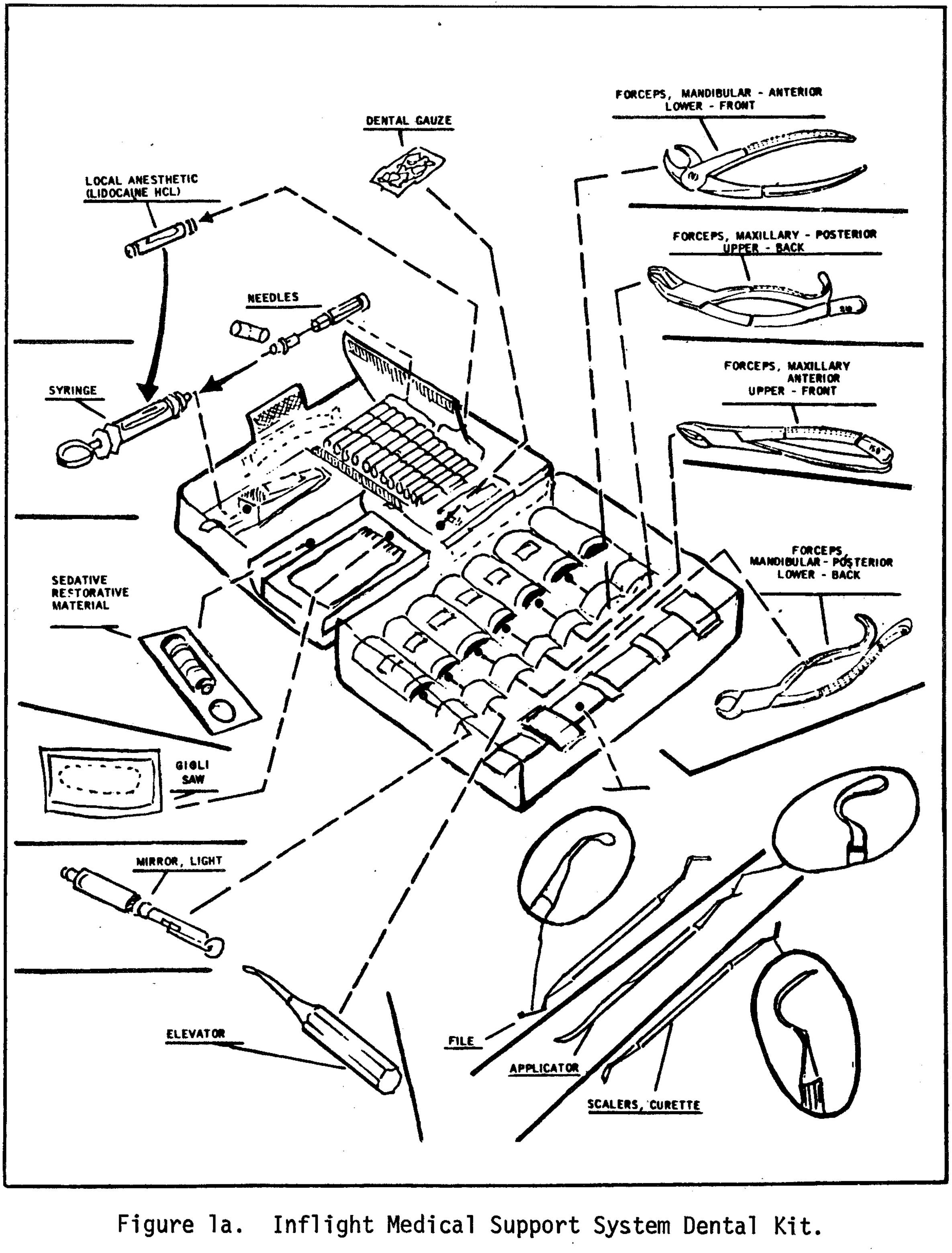

Figure 1a. Inflight Medical Support System Dental Kit.

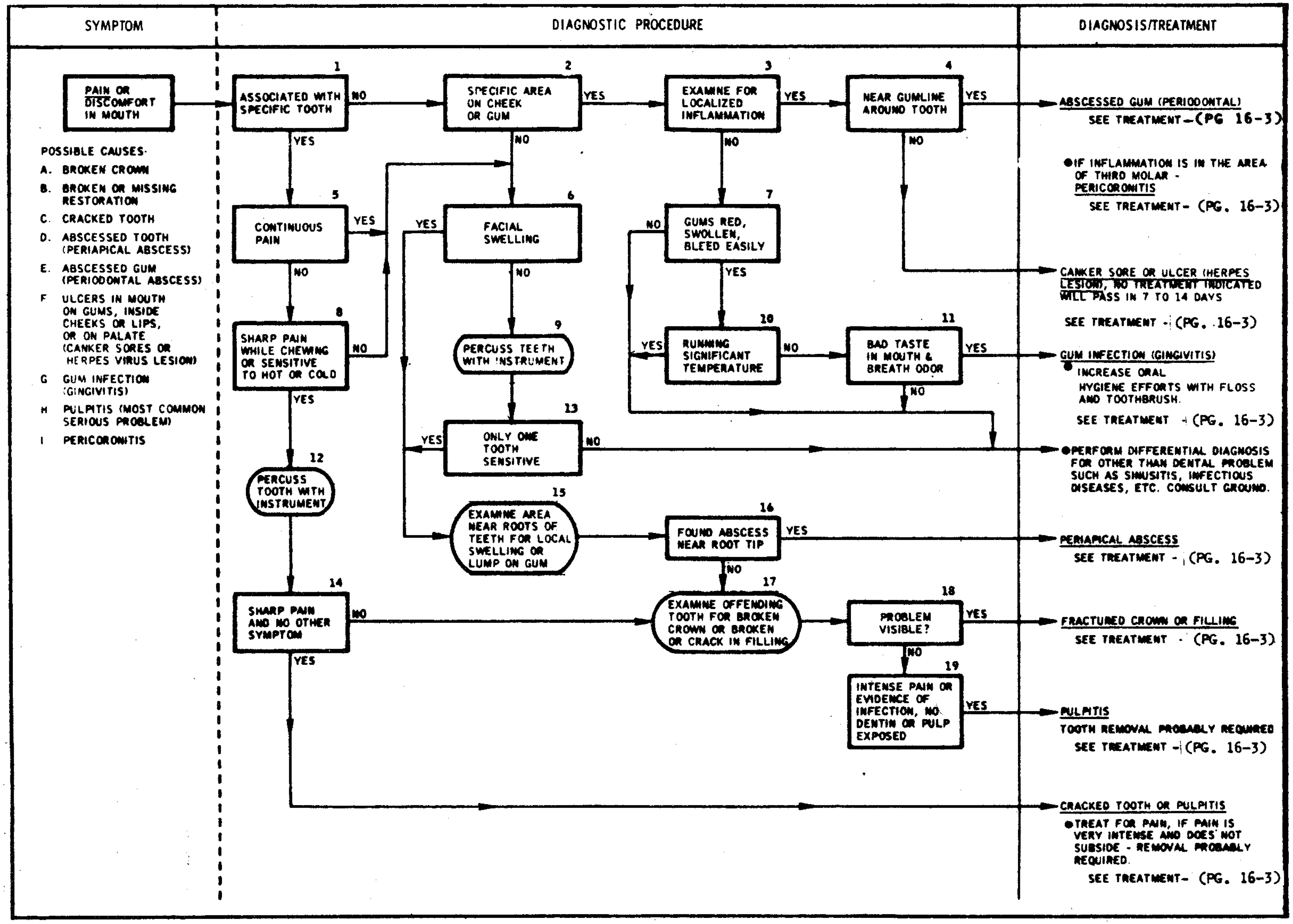

Figure 1b. Diagonostic Data - Dental.

CAUSE	SYMPTOMS	TREATMENT PROCEDURE	REMARKS
PULPITIS → EARLY	• DULL PAIN (INTERMITTENT) • SENSITIVE TO PERCUSSION HEAT AND COLD	• MAY REVERSE, USE ANALGESICS - • IF NOT, REMOVAL MAY BE NECESSARY.	ANTIBIOTICS MAY BE PRESCRIBED BY GROUND
PULPITIS → LATE (INFLAMMATION OF DENTAL PULP)	• SHARP PAIN (CONTINUOUS) • HEAT OR PERCUSSION INCREASES PAIN - • COLD DECREASES OR INCREASES PAIN • ASPIRIN OR DARVON DOES NOT RELIEVE PAIN.	• REMOVE TOOTH - SEE (PG 16-7) • PROBABLY NO TISSUE SWELLING.	
TOOTH DECAY (CARIES) [UNLIKELY CAUSE DUE TO TIME REQUIRED TO DEVELOP.]	• MILD PAIN (INTERMITTENT OR CONTINUOUS) • CAVITATION OF ENAMEL • BROWNISH - BLACK SPOT • HEAT, COLD, OR SWEETS MAY ELICT PAIN	• IDENTIFY OFFENDING TOOTH • EMPLOY LOCAL ANESTHESIA (16-6) • REMOVE SOFT DECAYED MATERIAL USING CURETTE • ISOLATE TOOTH WITH GAUZE PACKS AND DRY OUT CAVITY. • MIX SEDATIVE RESTORATIVE MATERIAL AND PACK INTO CAVITY WITH APPLICATOR • HAVE PATIENT BITE WHILE CEMENT IS SOFT, REMOVE EXCESS USING CURETTE • BITE AGAIN.	SEE MIXING PROCEDURES PG 16-5
CROWN FRACTURE, BROKEN OR MISSING FILLING	• PART OF TOOTH VISIBLY MISSING	• FILE OFF ROUGH EDGES OF BROKEN TOOTH USING FILE • MIX SEDATIVE RESTORATIVE MATERIAL AND COVER EXPOSED AREA • SMOOTH SURFACE	BITE DOWN TO CHECK OCCLUSION.
CRACKED TOOTH	• SEVERE PAIN WHEN CHEWING • MAY HAVE SYMPTOMS OF 2a - EARLY	• IF PAIN PERSISTS - REMOVE TOOTH - SEE (PG 16-7)	CRACK COULD HAVE GONE UNDETECTED ON X-RAYS.
PERIAPICAL ABSCESS (INFECTION AT APEX OF TOOTH)	• TOOTH MAY FEEL ELONGATED TO PATIENT. • PERCUSSION MAY ELICT SHARP PAIN • AREA OF POINTED SWELLING.	• INDUCE DRAINAGE OF PUS BY: (A) INCISION OF PUS POCKET, OR (B) DIGITAL PRESSURE ON GUM NEAR ROOT OF TOOTH. • IF PAIN PERSISTS - REMOVE TOOTH. SEE (PG 16-7)	ANTIBIOTICS MAY BE PRESCRIBED BY GROUND. PAIN WILL SUBSIDE UPON RELEASE OF PUS PRESSURE.
PERIODONTAL ABSCESS (GUM INFECTION)	• DULL THROBBING PAIN - SHARP PAIN WHEN BITING. • TENDERNESS OF SURROUNDING TISSUE	• PROBE AROUND TOOTH WITH CURETTE • REMOVE ANY FOREIGN OBJECT • INDUCE DRAINAGE OF PUS BY INCISION • RINSE WITH WARM WATER	ANTIBIOTICS MAY BE PRESCRIBED BY GROUND.
PERICORONITIS (INFLAMMATION OF GUM FLAP)	• PAIN ON OPENING MOUTH • CONTINUOUS DULL ACHE AND SWELLING AROUND LOWER THIRD MOLAR	• CLEAN UNDER TISSUE FLAP • BRUSH THOROUGHLY, RINSE AND FLOSS • RINSE VIGOROUSLY WITH WARM WATER.	ANTIBIOTICS MAY BE PRESCRIBED BY GROUND. BECOMES MORE COMFORTABLE IN 24-36 HRS.
APHTHOUS ULCER (WHITE SPOT ON ORAL MUCOSA)	• DISCOMFORT IS SOMETIMES MISTAKEN FOR TOOTHACHE	• NO TREATMENT IS INDICATED - NORMAL HEALING OCCURS IN 7 TO 14 DAYS.	ANTIBIOTICS ARE USUALLY OF NO VALUE.
CANKER SORE (RED ULCER)	• BURNING SENSATION NOT SHARP PAIN		

Figure 1c. Treatment Data - Dental.

Laboratory detectable intraoral changes can precede clinical manifestations of acute and chronic infectious disease. Clinically detectable alterations of oral tissue can identify changes caused by local and/or systemic disorders of microbial and nonmicrobial origin.

Oral hygiene procedures consisted of brushing the teeth two minutes twice a day and flossing once a day. Tooth brushes with multitufted, nylon, bristles were used in conjunction with an ingestible dentifrice[1] and thin, unwaxed dental floss. Irrigating devices, mouthwashes, topical fluorides or other oral medication were not used.

All crewmen were placed on a space-food diet at about 21 days preflight. The backup crewmen continued on the space diet until launch and the prime crewmen until 18 days after recovery.

Equipment and Procedures

Eighteen astronaut crewmembers making up the prime and backup crews for the three Skylab missions were monitored for quantitative changes in oral microorganisms, saliva partitions considered potentially important to oral health, and alterations in clinical indices of oral health and preexisting dental disease.

Microbiological assessments

Specimen collection. Oral specimens were collected from the crewmembers weekly or semiweekly from three intraoral sites from 31 days preflight to 18 days postflight for Skylab 2, from 51 days preflight to 20 days postflight for Skylab 3, and from 57 days preflight to 17 days postflight for Skylab 4. All collections took place between 7 a.m. and 8 a.m., before oral hygiene procedures or breakfast.

The specimens included dental plaque, crevicular fluid (exudate absorbed from the gingival sulcus area), and stimulated saliva. These parameters were selected because of their ultimate relation to the development of dental caries, periodontal disease, and alveolar bone loss.

Dental plaque was removed using a modification of the technique by Jordon *et al.* (1). Crevicular fluid was obtained by inserting a paper point into the gingival sulcus of an upper bicuspid according to the method of Brown *et al.* (2). Each specimen was placed aseptically

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[1] Ingestible dentifrice developed by Ira Shannon, D.D.S., M.S., Veterans' Administration Hospital, Houston, Texas

into a sterile tube containing 2 milliliters of 0.1 percent peptone and 0.85 percent sodium chloride. The peptone-saline solution served as both a transport and dilution medium.

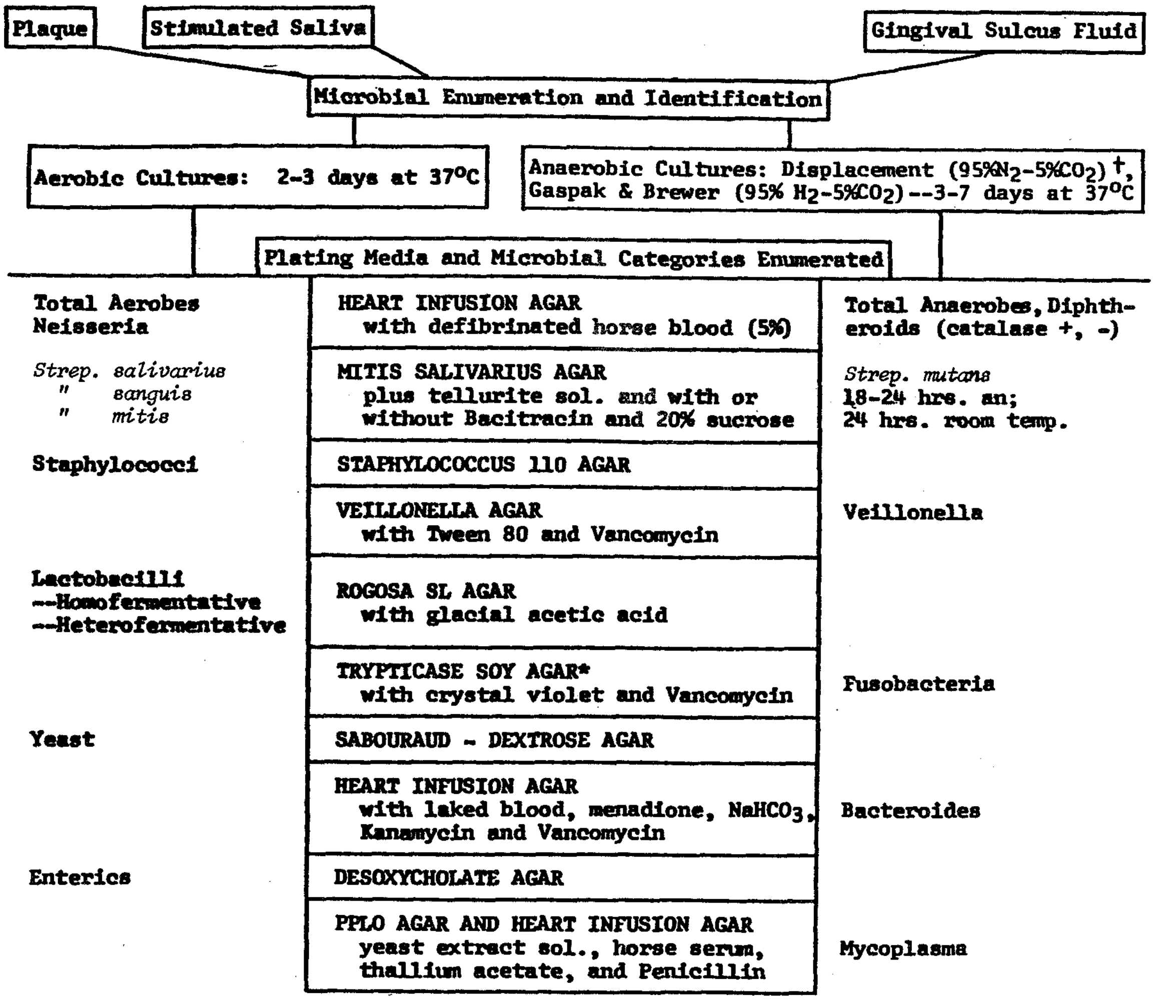
To produce stimulated saliva, the crewmembers chewed sterile paraffin and expectorated into a sterile jar until a 5 milliliter indicator mark was reached. The time required for each crewman to collect this volume was recorded and used to calculate the saliva flow rate.

All specimens were transported in cracked ice to the University of Texas Dental Science Institute for immediate processing which occurred about one hour after collection.

Specimen processing. Serial ten-fold dilutions of each specimen were plated onto a variety of bacteriologic media (3,4,5,6,7,8,9,10,11,12, 13,14) for the enumeration of up to seventeen microbial categories. Duplicate platings were incubated at 37° C either aerobically or anaerobically. The bacteriologic media, microbial categories, and anaerobic procedures are shown in figure 2.

Specific microbial types from selective and differential media were verified by subculture and by pertinent physiologic reactions when necessary.

In addition to the microbial assessments, stimulated saliva was used to determine total protein, secretory IgA, and lysozyme. Salivary protein determinations were made by the Lowry procedure (15). Secretory IgA was assayed by electroimmunodiffusion (16) where the samples are electrophoresed through a medium containing monospecific antisera. Plates were precoated with 0.1 percent agarose in 0.05 percent glycerol and layered with buffered agarose containing antisera. Wells were fill filled with standards or saliva. Samples were electrophoresed until the point of equivalence with the highest standard was attained. The plates were then processed for staining and the migration distances were measured. Samples with values beyond the standard range required dilution. A plot of log concentration versus log migration distance yielded a linear curve for quantification (17). Lysozyme values were determined by radial quantitative diffusion using heat-killed *Micrococcus lysodeikticus* cells as a substrate according to the procedures of Osserman and Lawlor (18). Plates were layered with a cell suspension in buffered molten agarose. Wells were cut and filled with standards or saliva. Diffusion was allowed to proceed overnight. Values were determined from a plot of log concentration versus diameter of lysed zone.



* BBL; other media-Difco
† Steel wool coated with acidified copper sulfate solution.

Figure 2. Flow chart for sampling and enumerating cultivable oral microorganisms.

The microbiologic enumeration and immunologic data were recorded for appropriate statistical analysis. Both a one-way and two-way unbalanced analysis of variance were used for multiple comparisons of individual, paired, and grouped data. Primary comparisons were made within three segments of data: 1) preflight-prespace diet (31 and 21 days preflight or 29 and 19 days preflight), 2) preflight-space diet (14 and 3 days preflight or 13 and 4 days preflight), and 3) recovery space diet (4, 13, and 18 days postflight from the prime crew only).

Clinical evaluations. Preflight clinical scores of dental plaque, calculus, and gingival inflammation were derived from clinical examinations of both prime and backup crews at 30, 53, and 57 days preflight for Skylab missions 2, 3, and 4, respectively. Comaparable recovery scores were obtained at clinical examinations at four days postflight for the prime crewmen. Dental plaque and calculus were removed at the preflight evaluation periods to adjust the test subjects to an equal baseline (score of 0) for comparisons of subsequent increments of plaque and calculus formation. The examinations were designed to determine changes in the amount of plaque and calculus that formed on the teeth, gingival response to the Skylab confinement, and teeth, bone, and tissue changes resulting from the space environment. Plaque, calculus, and inflammation indices were derived from the findings.

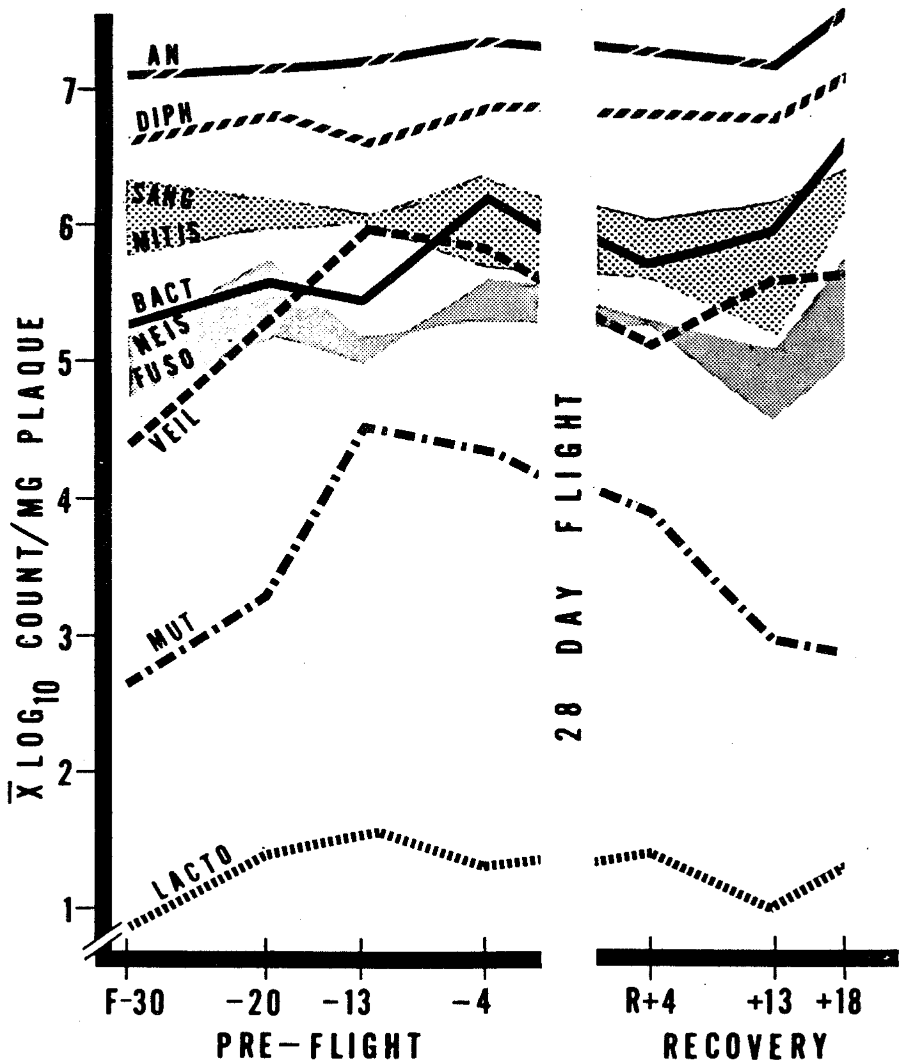
A plaque score was obtained for each astronaut by the use of disclosing wafers which stained the plaque adhering to the tooth surfaces. Calculus scores were obtained for each crewmember by dividing the number of tooth surfaces that had calculus by the number of teeth. The inflammation index was scored according to the method of Loe and Silnes (19) which graded the gingivae surrounding each tooth.

Dental radiographs were made of each crewmember at 6 months and 30 days preflight to provide baseline records for subsequent comparison. A complete series of oral radiographs were taken at 6 months preflight. To minimize radiation exposure, only bitewing radiographs were taken at 30 days preflight.

The clinical evaluations were statistically compared by "t" analysis using both the means difference and difference between means statistics (20).

Results

In Skylab 2 the microbial data illustrated in figure 3 shows increases in various anerobic components, *i.e., Bacteriodes* sp., *Veillonella* sp., *Fusobacterium* sp. Other increases were in *Neisseria* sp. and *Streptococcus mutans*.



KEY:

AN = Total anaerobes
DIPH = Diphtheroids (catalase positive and catalase negative gram-positive nonlactobacillus rods)
BACT = *Bacteroides* sp.
FUSO = *Fusobacterium* sp.
VEIL = *Veillonella* sp.
MITIS = *Streptococcus mitis*
SANG = *S. sanguis*
MUT = *S. mutans*
LACTO = *Lactobacillus* sp.
NEIS = *Neisseria* sp.

Figure 3. Microbial counts from dental plaque of the prime crewmembers of Skylab 2.

Fewer microbial changes were noted in Skylab 3. For example, in the graph of stimulated saliva (figure 4) the anerobic components showing increases were *Veillonella* sp., *Fusobacterium* sp., *Leptotrichia* sp., and *Mycoplasma* sp. *S. mutans* counts were variable. However, in this flight *Staphlococcus aureus* and enteric organisms showed increasing trends toward the latter stages of sampling.

The microbial data from the Skylab 4 mission were very similar to that of the Skylab 3 mission as is indicated in figure 5. The anerobic components to show increases in the gingival sulcus fluid in this slide were *Bacteroides* sp. and *Veillonella* sp. There was also a rise in *S. sanguis* and *Neisseria* sp.

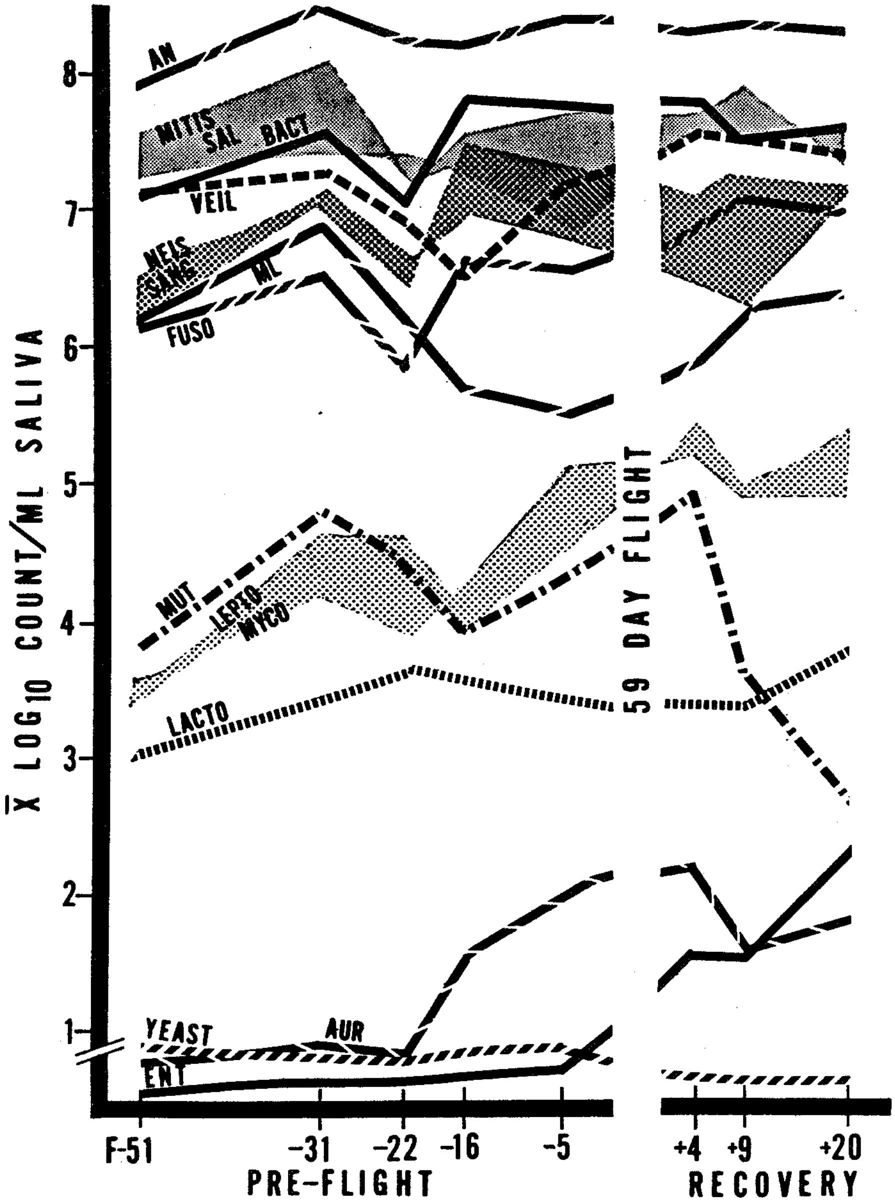
Figure 6 represents the cumulative preflight data of all eighteen crewmen, before and after they were placed on the carbohydrate enriched space diet. At these levels of significance expressed on a percentage basis, there were significant increases after diet of the following total anerobes, Diphtheroids, *S. sanguis*, *Neisseria* sp., *Bacteroides* sp., *Veillonella* sp., and *Fusobacterium* sp. Most of the oral microbial changes noted during each mission appeared to be associated with diet change as evidenced by the statistically significant post diet increases.

The saliva partitions assayed in this study of the prime crew of Skylab 2 are shown in figure 7. Saliva flow rates, salivary lysozyme, and protein concentration levels remained relatively constant throughout this period. But the secretory IgA levels showed pronounced increases beginning just prior to flight and continuing throughout the postflight sample period. It is believed that these changes were probably due to responses to a subclinical viral infection.

Figure 8 displays the mean values for changes in salivary partitions of the prime crewmembers of Skylab 3. Secretory IgA showed increases and these increases occurred concurrently with saliva flow rate increases and salivary protein decreases. Reasons for the latter changes are presently unexplained.

In the Skylab 4 mission secretory IgA levels again increased and the levels of protein and lysozyme as well as saliva flow rates showed trends similar to the Skylab 3 flight (figure 9). The increase in secretory IgA in the crewmen for the Skylab 4 mission occurred in only two of the three crewmen (figure 10). The IgA levels of the Scientist Pilot remained relatively constant.

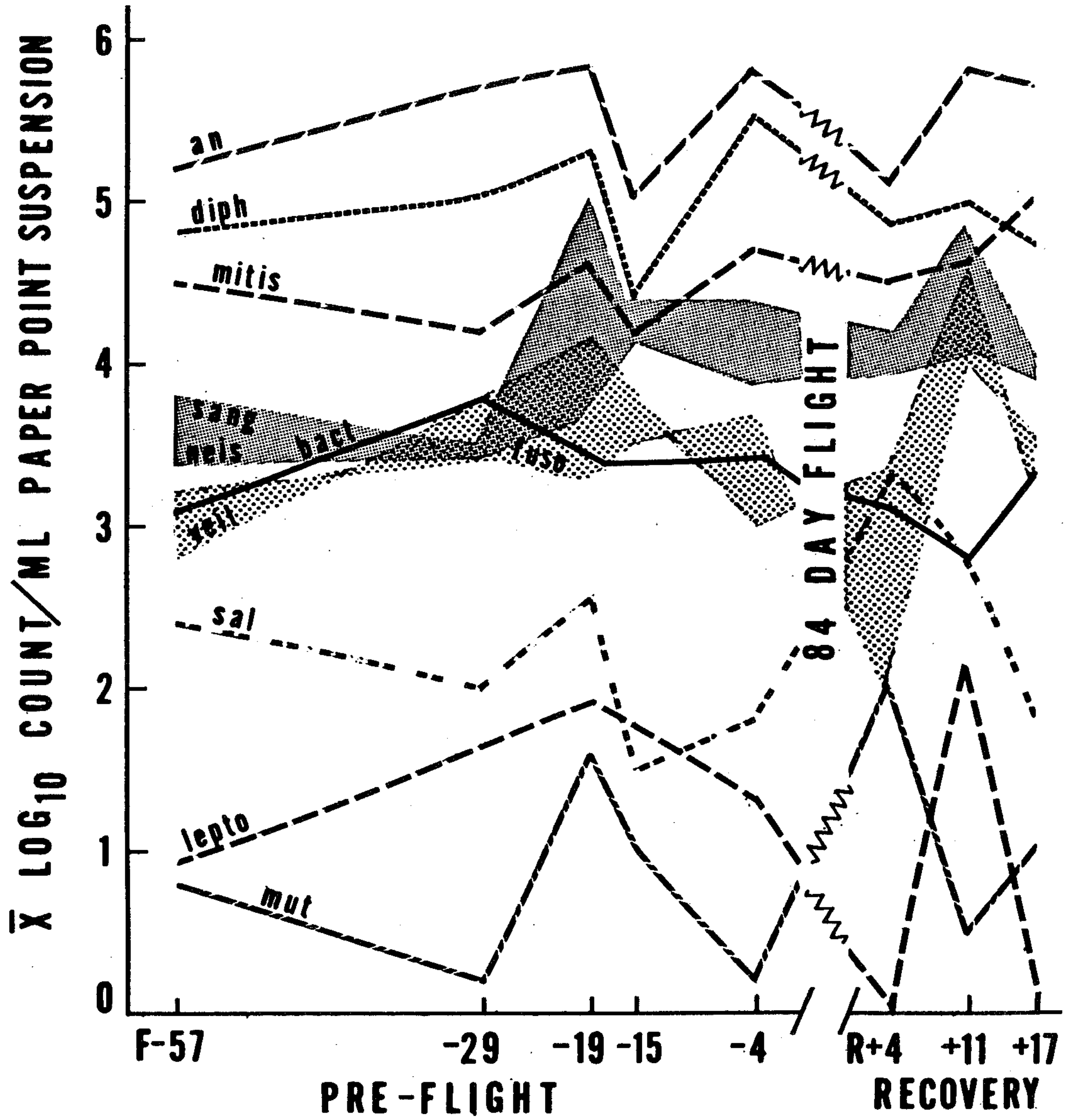
A comparison of clinical scores of oral health before and after the Skylab 4 mission (figure 11) revealed prominently elevated increments of dental calculus and gingival inflammation postflight as compared with the preflight values. This trend was observed for all missions.



KEY: Preflight values are means of both the prime and backup crewmembers. Recovery values are means of the prime crew.

AN	= Total anaerobes	SANG	= *S. sanguis*
MITIS	= *Streptococcus mitis*	FUSO	= *Fusorium* sp.
SAL	= *S. salivarius*	MUT	= *S. mutans*
BACT	= *Bacteriodes* sp.	LEPTO	= *Leptotricia* sp.
VEIL	= *Veillonella* sp.	MYCO	= mycoplasma
NEIS	= *Neisseria* sp.	LACTO	= *Lactobacillus* sp.
		ML	= streptococcus (mutans-like)

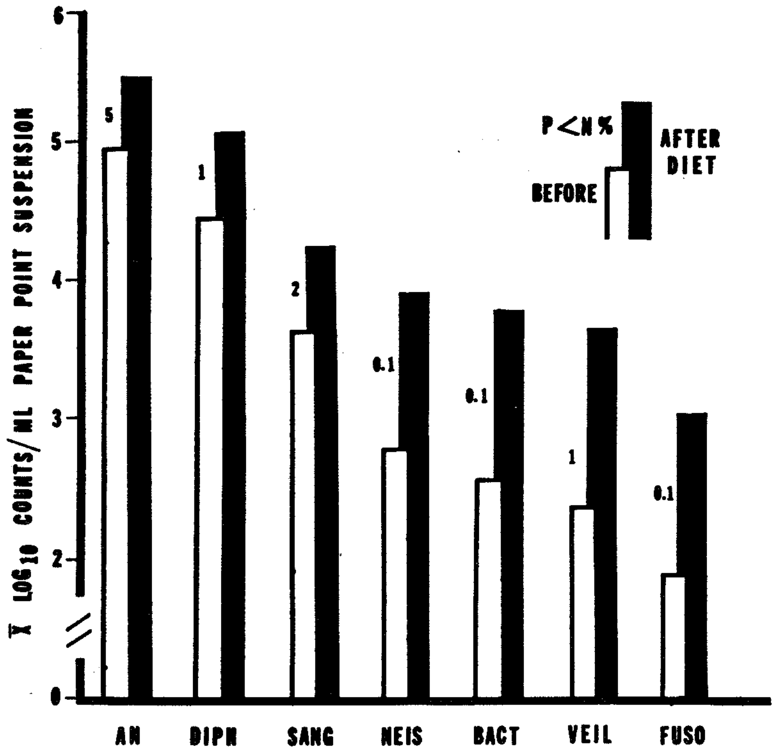
Figure 4. Microbial counts from stimulated saliva before and after the Skylab 3 Mission.



KEY: Preflight values are means of both the prime and backup crewmembers. Recovery values are means of the prime crew.

AN	= Total anaerobes	SAL	= *S. salivarius*
DIPH	= Diptheroids	BACT	= *Bacteroides* sp.
MITIS	= *Streptococcus mitis*	FUSO	= *Fusobacterium* sp.
NEIS	= *Neisseria* sp.	LEPTO	= *Leptotrichia* sp.
SANG	= *S. sanguis*	MUT	= *S. mutans*

Figure 5. Microbial counts from gingival fluid before and after the Skylab 4 mission.



KEY:

AN = Total anaerobes
DIPH = Diphtheroids
SANG = *Streptococcus sanguis*
NEIS = *Neisseria* sp.
BACT = Bacteroides sp.
VEIL = *Veillonella* sp.
FUSO = *Fusobacterium* sp.

Figure 6. Cumulative Microbial Counts from the gingival fluid of 18 crewmen before and after space diet initiation prior to three Skylab flights.

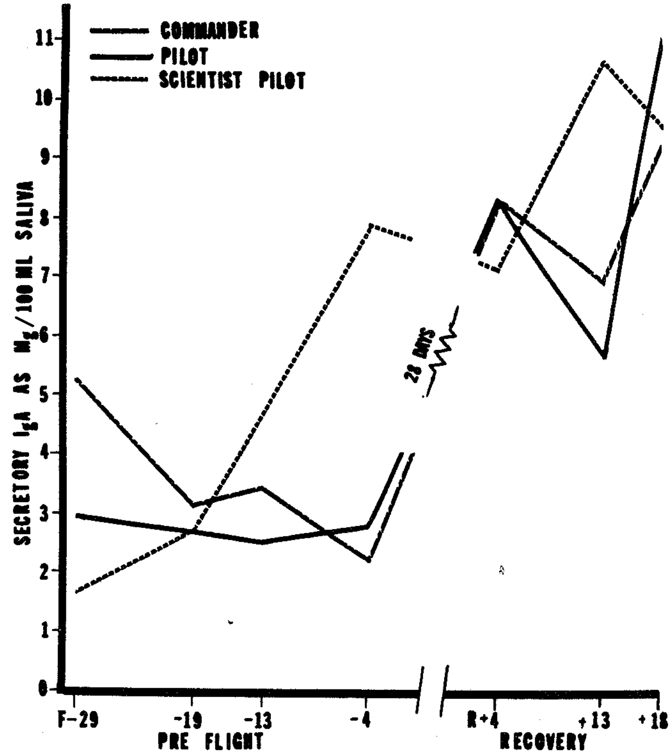
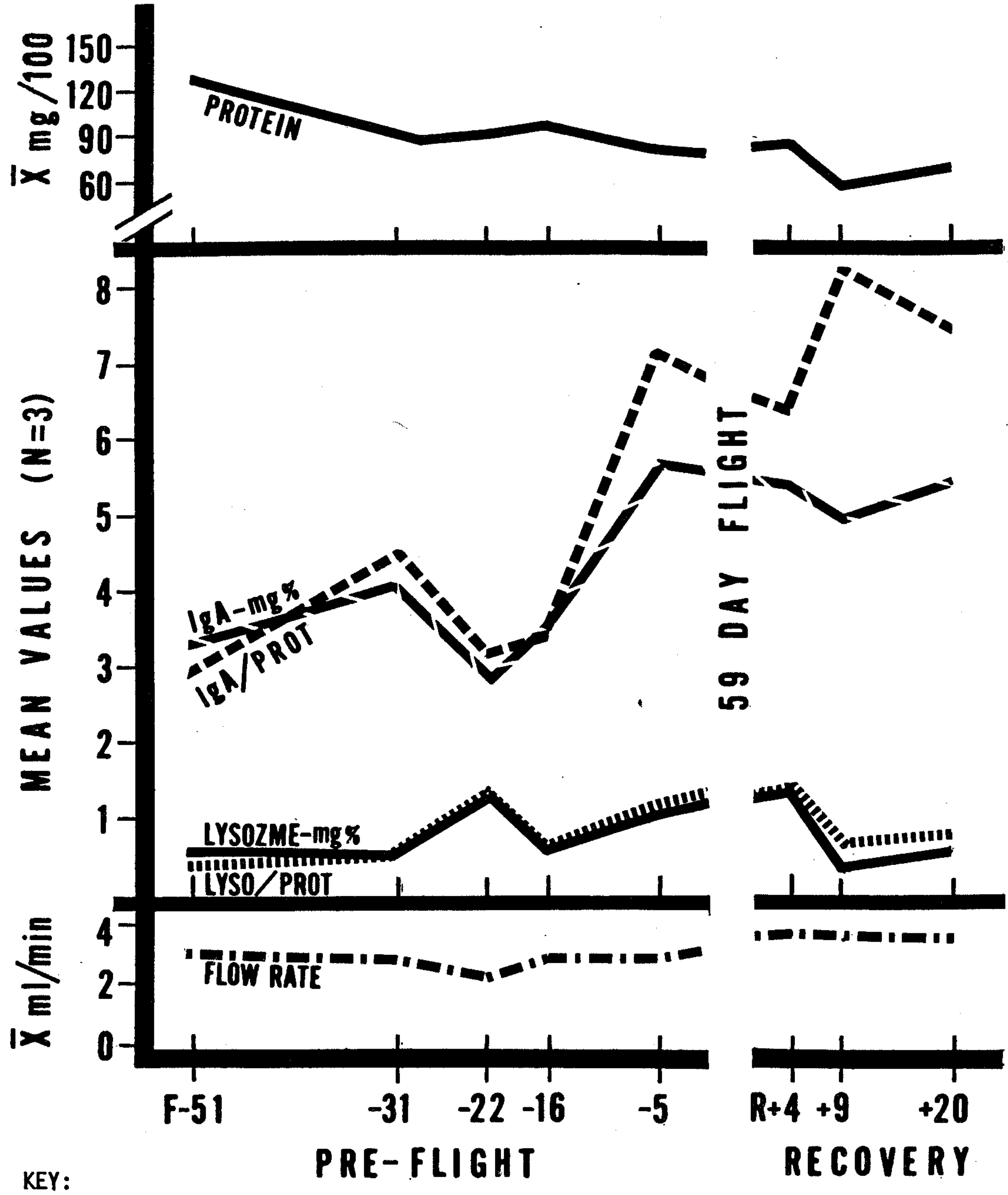


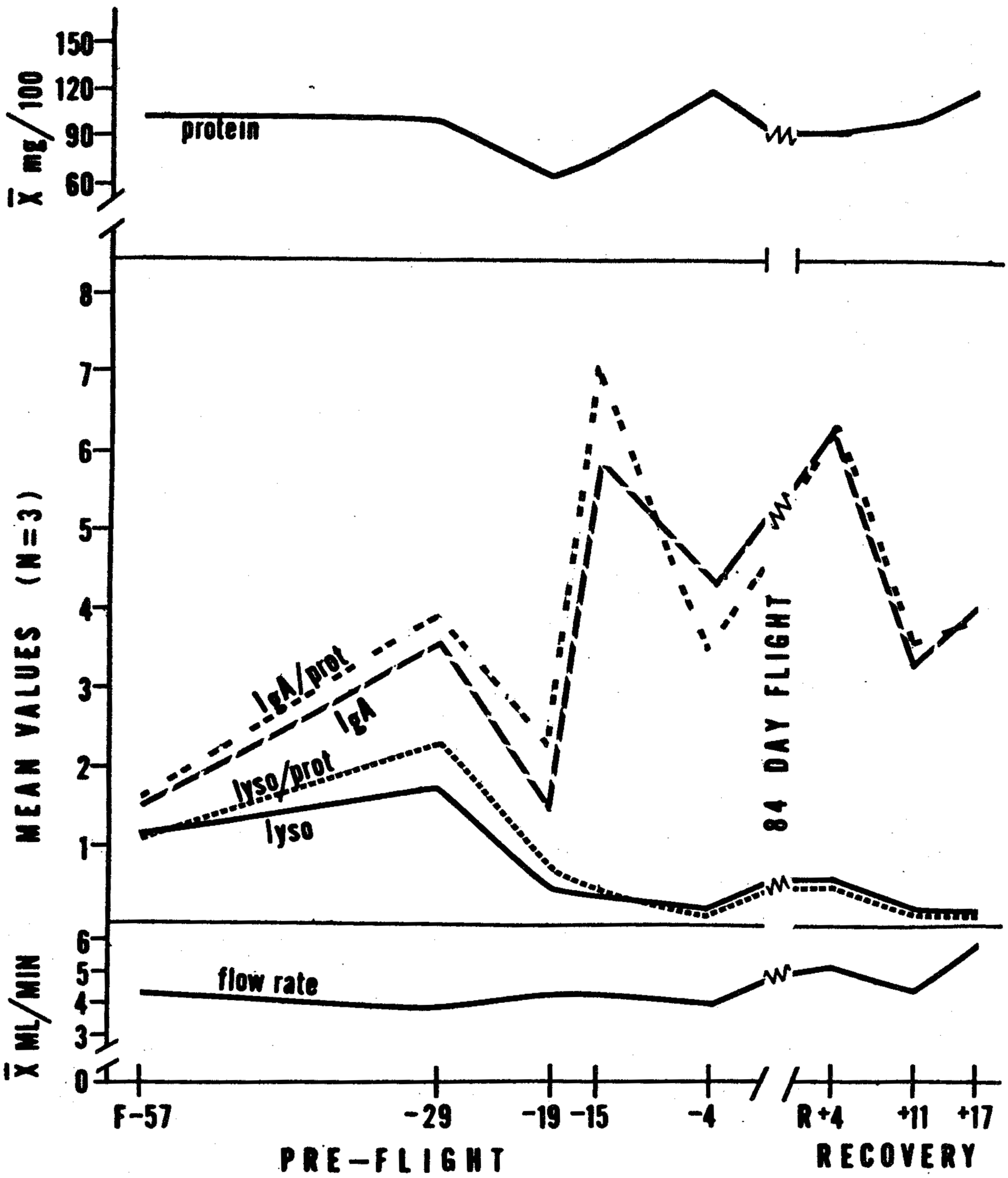
Figure 7. IgA levels in the stimulated saliva of the individual prime crewmembers before and after the Skylab 2 mission.



KEY:

IgA/PROT = Ratio of secretory IgA to total saliva protein concentration.
LYSO/PROT = Ratio of salivary lysozyme to total saliva protein concentration.

Figure 8. Saliva protein concentrations, secretory IgA and lysozyme levels and saliva flow rates of the prime crewmembers of Skylab 3.



KEY:

IgA/PROT = Ratio of secretory IgA to total saliva protein concentration.
LYSO/PROT = Ratio of salivary lysozyme to total saliva protein concentration.

Figure 9. Saliva protein concentrations, secretory IgA and lysozyme levels, and saliva flow rates of the prime crewmembers of Skylab 4.

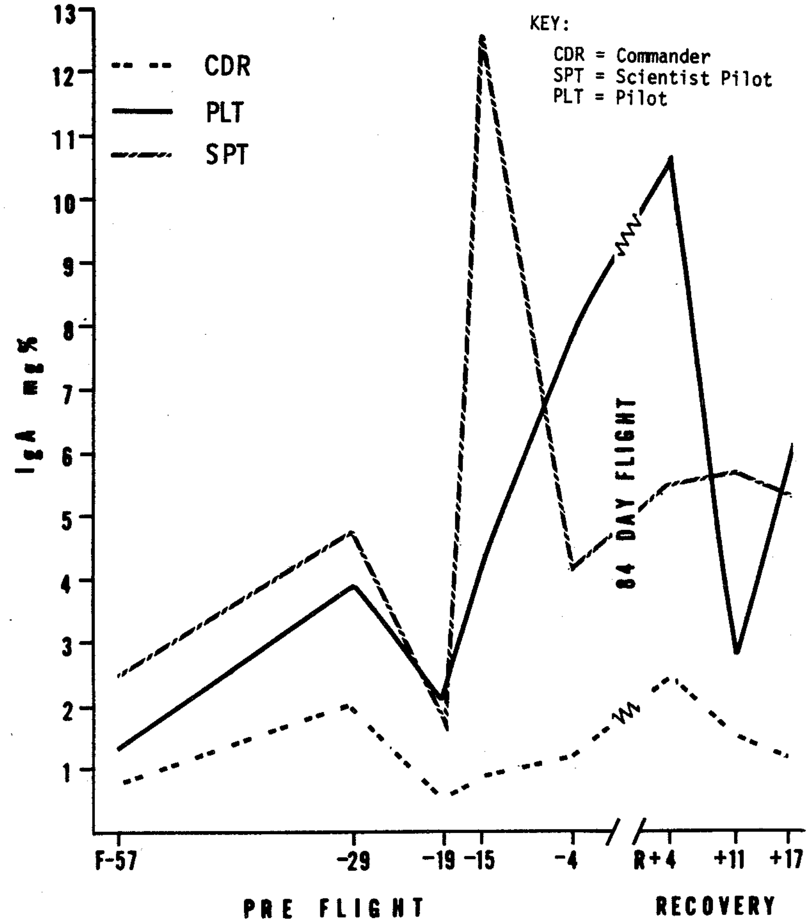


Figure 10. Secretory IgA levels of the individual crewmembers of Skylab 4.

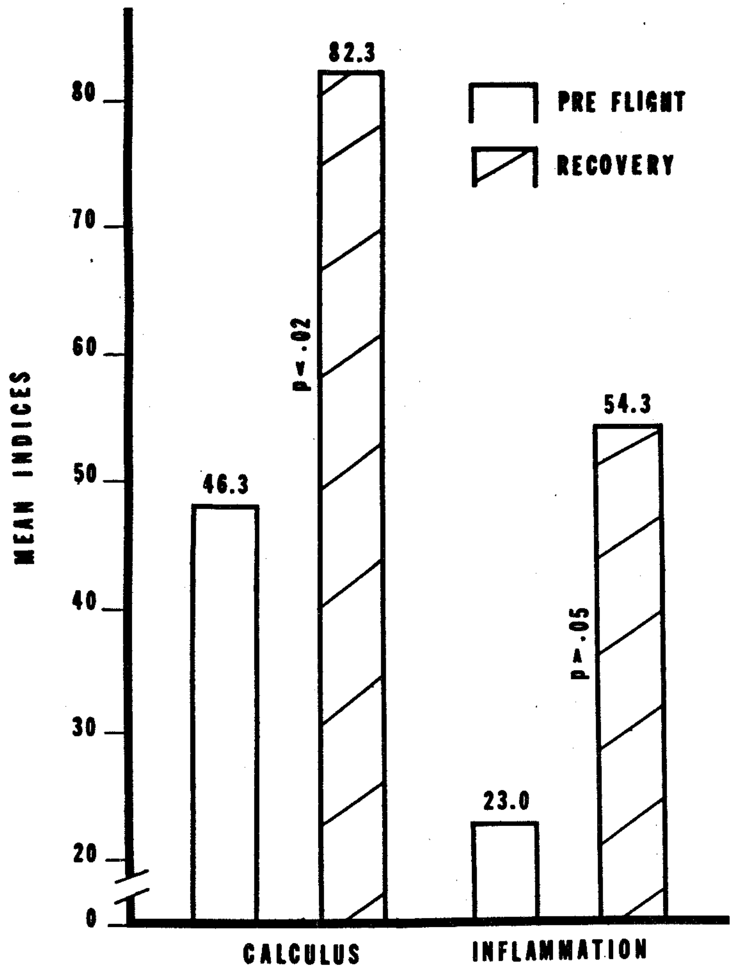


Figure 11. Mean clinical scores of Dental Calculus and Gingival Inflammation of the prime crewmembers of Skylab 4.

While the overall oral health level of all crewmen remained very good postflight, some deterioration had occurred as measured by these indices.

Discussion

The oral microbiologic, immunologic, and clinical results of the Skylab series of manned space flight missions were relatively consistent. Oral microbial changes usually occurred after the incorporation of the space diet prior to flight. Statistical comparisons of cumulative preflight data from the 18 (prime and backup) crewmembers, before and after diet inclusion, revealed diet relatedness for the majority of the microbial increases observed during the missions. Some of the changes, although apparent after the inclusion of the diet during the preflight period, were more pronounced after flight. However, the postflight values were excluded in the diet related analysis to avoid any possible flight influence.

Increases in secretory IgA observed in two of the Skylab 4 crewmembers were observed in all three crewmembers of Skylabs 2 and 3. As in the previous studies, the changes were believed to result from subclinical infections. Concurrent fluctuations in salivary protein, lysozyme and saliva flow rates, also observed in previous studies, are unexplained.

Increased increments of dental calculus and gingival inflammation observed in these studies were consistent with the exception that the changes were not observed in the Skylab 3 flight indicating that clinical changes in oral health in space flights correspond to those under more conventional circumstances; *i.e.*, individuals free of oral health problems are less susceptible to detrimental changes under a specific challenge than those with preexisting dental problems.

Conclusion

Skylab crewmembers were monitored for mission related effects on oral health. Those laboratory and clinical parameters considered to be ultimately related to dental injury were evaluated. Of these, the most distinctive changes noted were:

- Increased counts of specific anaerobic and streptococcal components, primarily of the saliva and dental plaque microflora.

- Elevations in levels of secretory IgA concurrent with diminutions of salivary lysozyme.

- Increased increments of dental calculus and gingival inflammation.

The microbial changes were mainly diet related rather than flight related. Elevations of secretory IgA were believed to result from a subclinical infection. Concurrent diminutions of salivary lysozyme are unexplained. The clinical changes in oral health were considered to be influenced more by a crewmember's preexisting state of dental health than by any health hazardous mission related effect.

Assuming no future clinical detection of mission-related intraoral complications, the most significant aspect of these investigations was the relative nonexistence of health hazardous intraoral changes.

ACKNOWLEDGMENT

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ANALYSIS OF THE SKYLAB FLIGHT CREW HEALTH STABILIZATION PROGRAM

J. K. Ferguson, Ph.D., G. W. McCollum, M.S.*, and B. L. Portnoy, M.D.†*

ABSTRACT

Throughout the Skylab Program, an extensive effort was made to reduce the probability of an illness occurrence in the flight crewmen. The Flight Crew Health Stabilization Program accomplished this objective by isolating the flight crew during preflight periods. In addition, the number of personal contacts with the crewmen was limited, and ill persons were not permitted to enter primary work areas.

Initially, all persons who required contact with the flight crewmen during a 21-day period before flight were identified. Physical examinations and immunizations were given to the identified personnel. Voluntary reporting and active surveillance were used to detect illness occurrences and exposures to illness among the primary contact personnel.

During the postflight period, the crewmen again were isolated and their contacts limited to medically approved personnel to reduce the occurrence of illness and to reintroduce the crewmen gradually to the normal environment. The methods and procedures used in the program are presented, together with a descriptive analysis of the surveillance data.

INTRODUCTION

A well defined Flight Crew Health Stabilization Program was first introduced into the space program on the Apollo 14 mission. The program was initiated following a number of prime crew illnesses and crew exposure to persons with infectious illnesses during mission critical periods. As a result of these incidences, it was recognized throughout the National Aeronautics and Space Administration that crew illness could cause loss in valuable crew training time, postponement of missions, or could even compromise crew safety and mission success.

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The purpose of the Flight Crew Health Stabilization Program was, therefore, to minimize the possibility of adverse alterations in the health of flight crewmen during the preflight, in-flight, and postflight periods. The Apollo 14 Flight Crew Health Stabilization Program was successfully completed without an illness occurrence in the crewmen. Following the Apollo 14 mission, the program was effectively used for the remainder of the Apollo missions.

The need for such a program became even more evident in the development of the Skylab missions. The extended periods of crew time in space planned for Skylab increased the probability of in-flight crew illness. The decision was made, therefore, to provide a comprehensive Skylab Flight Crew Health Stabilization Program.

PROCEDURE

A 21-day isolation period was established for the Skylab crewmen prior to the launch of each mission. This isolation period was chosen to cover the incubation period of the majority of infectious diseases. A seven-day postflight isolation period was added to protect the crewman from any increased susceptibility to infectious diseases as a result of the lengthy mission. Additionally, postflight illness in the crewmen would have been detrimental to the understanding of medical results and the transfer of information to the crewmen of the next mission. The principal objective of the program was to reduce the probability that a crewman would come into contact with an infectious disease agent during the critical time periods of each mission. The initial steps taken to accomplish this objective were to:

- Establish the primary work areas of the crewmen during the isolation periods.
- Establish isolated crew housing at both the Johnson Space Center and at the Kennedy Space Center with methods to prevent crew exposure to infectious disease agents.
- Establish a medical program for those personnel who were required to work with the crewmen during the isolation period.
- Establish a Medical Surveillance Office as the coordination center for the operational aspects of the program (table I).

Each functional area at the two National Aeronautics and Space Administration Centers identified their personnel who would require access to the crew during the isolation period. Personnel requiring

TABLE I. SKYLAB FLIGHT CREW HEALTH STABILIZATION PROGRAM

Primary Contacts

Class A and Class B

Illness Reporting (Voluntary)

Crew

Living Quarters

- Mobile Trailers (JSC)
- Crew Quarters (KSC)

Food

Travel

(Crew Surgeon)

Medical Surveillance Office

Program Coordination

Training

Records and Data

Medical Status Reports

Primary Work Areas

Active Surveillance

Security

Preventive Measures

- Surgical Masks
- Biorespirators
- Air Filters

Clinic

Medical Examinations

PC Qualification - Disqualification

Badge Control

direct crew access (within two meters) were known as class A primary contacts. Those who worked in primary work areas, but were not in direct contact of the crewmen, were called class B primary contacts.

For each primary work area identified, the area was inspected and procedures were established to minimize the possibility of crew exposure to pathogenic microorganisms. Positive air pressures and 80 percent (ASHRAE[1]) air filters were used in the principal training area. A security guard and a nurse were stationed at the door of the primary work areas on the days that crewmen would be in the area. On these days, only properly badged primary contacts were allowed to enter the area and a brief medical screening was given to class A primary contacts by the nurse as the only active surveillance provided in the program. All class A primary contacts were required to wear surgical masks when in the presence of the crewmen. Biorespirators were available for use by nonprimary contacts if an emergency occurred. Crew conferences with nonprimary contacts were accomplished by closed circuit television.

Crew housing at the Johnson Space Center was provided by two mobile homes placed inside a large building. A third mobile home adjacent to the building served as the food service center. All food and drink consumed by the crew during the isolation period was specially prepared Skylab food. Quality control had been designed into the food program, and it was, therefore, not necessary to add additional controls. A fourth mobile home was available for isolation of any crewmen who might become ill. Housing at the Kennedy Space Center was provided in the existing crew quarters area, and high efficiency particulate air (HEPA) filters were used in these living areas. Measures were taken to prevent crew exposures to illness while traveling between primary work areas. Nonprimary contacts were kept 100 feet and downwind from the crewmen. Biorespirators were near the crewmen at all times to be used if an emergency occurred.

The medical program for the primary contacts consisted of an extensive initial physical examination with laboratory screening (appendix A). Immunizations were required for those persons who were not immune to a selected group of infectious diseases. After the examination the records of each person were reviewed by a physician, and the individual was either approved or disapproved as a primary contact. Further scheduled examinations were provided later in the program only for

[1]American Society of Heating, Refrigerating and Air-Conditioning Engineers

class A primary contacts, which also included food handlers, maids and other specialized personnel having close direct, or indirect, contact with the crewmen.

On completion of the initial medical examination, all primary contacts were instructed by letters, brochures, and meetings to report any illness, or contact to an infectious illness, to the Medical Surveillance Office. Primary contacts who reported medical problems related to infectious illness were referred to the clinic for medical examination. If a primary contact was found to have an infectious illness, he was temporarily withdrawn from the program and the primary work area. The primary contact did not return to the work area until a medical examination indicated that the infection was no longer present. Medical surveillance of the primary contacts and illness reporting were continued throughout each mission to provide epidemiological support data for any crew illness occurring during the mission.

A report form was completed by the clinical staff for each illness occurrence (appendix B). The report was forwarded to the Medical Surveillance Office to be coded for the type of illness by a predetermined list of operational definitions of infectious illness (appendix C). An analysis of these data was performed.

RESULTS AND DISCUSSION

The list of approved primary contacts changed throughout the Skylab program. Names were added or deleted as required. The population of primary contacts for each flight was assumed to be the number recorded on the master list at the end of each mission (table II). At all times class A primary contacts were only slightly less in number than class B primary contacts. The total number of primary contacts ranged from 620 to 709 throughout the Skylab program until 21 days into the Skylab 4 mission; program coverage provided only for 140 personnel for the remainder of the Skylab 4 mission. In all cases, the great majority of primary contacts were located at the Johnson Space Center.

Active surveillance of class A primary contacts produced a total of only 23 referrals to the clinic from a total of 3483 examinations (table III). The small number of possible illnesses discovered by this procedure suggests that active surveillance indirectly influenced the primary contacts to report their illnesses voluntarily. In this indirect way, the presence of a nurse at the entrace of the work area may have protected the crewmen from infectious agents.

TABLE II. POPULATION OF PRIMARY CONTACTS FOR THE SKYLAB MISSIONS

Skylab Mission	NUMBER OF PRIMARY CONTACTS Class A	Class B	Total	LOCATION OF PRIMARY CONTACTS JSC	KSC	Other
2	280	340	620	561	36	23
3	316	393	709	620	33	56
4(Pre-)*	300	333	633	550	35	48
4(Post-)†	108	32	140	121	0	19

Legend:

* = Preflight plus first 21 mission days
† = Mission day 22 through 7 days after recovery

TABLE III. ACTIVE SURVEILLANCE OF CLASS A PRIMARY CONTACTS

Active Surveillance	Skylab Mission 2	3	4	Total Number
Class A Contacts Examined	1124	1104	1255	3483
Contacts Referred to Clinic	4	0	19	23
Examining Days	29	22	29	80
Contacts Examined/Day (avg)	39	50	43	44

A total of 197 illnesses were reported to the Medical Surveillance Office during the Skylab program. Of these reports, 88 percent were reported from the Johnson Space Center and the remaining 12 percent were from the Kennedy Space Center (table IV).

The rate of illness reported by the primary contacts declined from Skylab 2 to Skylab 4 (table V). During Skylab 2 the rate of illness reporting was 10.7 illnesses/1000 primary contacts/week. During Skylab 3 the rate declined to 8.4 and during Skylab 4 to 6.7. The drop in illness rate is especially dramatic since the lowest rates occurred during the winter season where most respiratory infections were expected.

TABLE IV. LOCATION OF PRIMARY CONTACTS REPORTING ILLNESS

Skylab Mission	Number of Illnesses Reported JSC	KSC	Total/Mission
2	67	3	70
3	61	20	81
4(Pre-)*	36	1	37
4(Post-)†	9	0	9
Total	173	24	197

Legend:

* = Preflight plus first 21 mission days
† = Mission day 22 through 7 days after recovery

TABLE V. RATE OF ILLNESS EVENTS REPORTED BY PRIMARY CONTACTS

Primary Contact Group	Skylab Mission 2	3	4(Pre-)*	4(Post-)†
Class A Contact	10.5‡	8.6	8.8	3.6
Class B Contact	10.9	8.2	4.8§	15.0§
Both	10.7	8.4	6.7	6.2

Legend:

* = Preflight plus first 21 mission days
† = Mission day 22 through 7 days after recovery
‡ = Rate expressed as number of illnesses reported per 1000 persons per week.
§ = Based on 5 or less events

The upper respiratory infection was by far the most frequently reported illness by primary contacts (table VI). Symptom complexes other than the upper respiratory infection were relatively low and equally distributed in number. All of the percentages were below 10 percent with the exception of the reported presence of fever which reached 14 percent on Skylab 3 and 11 percent on Skylab 4.

TABLE VI. TYPES OF ILLNESSES REPORTED BY PRIMARY CONTACTS

Symptom Complex*	Total Reported (All Missions) Number (2 Flights)	Total Reported (All Missions) Percent of Total (2 Flights)	Percent Reported Per Skylab Mission 2	3	4
Upper Respiratory Infection	159	81	79	83	80
Bronchitis	8	4	6	2	4
Pneumonia	0	0	0	0	0
Upper Enteric Illness	13	7	9	4	9
Lower Enteric Illness	13	7	6	9	4
Fever Present	20	10	6	14	11
Headache Present	11	6	4	9	2
Skin Infection Present	12	6	7	7	2
Other Infectious Illness	2	1	1	1	0

*One illness may contain more than one symptom.

As with the illness reporting, the vast majority of reports of contact to illness originated from the primary contacts at the Johnson Space Center (table VII). Of a total of 73 reports only two came from other sources on the Skylab 2 and Skylab 4 missions. Skylab 3 contacts to illness are not reported here due to an error in recording reports. The rates of reporting contacts to illness are shown in table VIII. Although Skylab 3 data are not available, the reporting trend appears to decrease in rate in the same manner as illness reporting.

Exposure to persons with upper respiratory infections was the most frequently reported contact with illness, with 57 percent and 67 percent reported for Skylab 2 and Skylab 4, respectively (table IX). A greater percentage of upper and lower enteric illness contacts were reported for Skylab 4 than for Skylab 2. None of the Skylab 4 reports involved skin infections while 18 percent of the Skylab 2 reports involved contact with skin infections.

TABLE VII. LOCATION OF PRIMARY CONTACTS REPORTING CONTACT TO AN INFECTIOUS ILLNESS

Skylab Mission	Number of Contacts Reported JSC	KSC	Total/Mission
2	49	0	49
4(Pre-)*	19	1	20
4(Post-)†	4	0	4
Total	72	1	73

Legend:

* = Preflight plus first 21 mission days
† = Mission day 22 through 7 days after recovery

TABLE VIII. RATE OF CONTACTS TO ILLNESS REPORTED BY PRIMARY CONTACTS

Primary Contact Group	Skylab Mission 2	4(Pre-)*	4(Post-)†
Class A	10.8‡	4.6	3.6§
Class B	4.7	2.8	0.0
Both	7.5	3.6	2.7§

Legend:

* = Preflight plus first 21 mission days
† = Mission day 22 through 7 days after recovery
‡ = Rate expressed as number of contacts to illness reported per 1000 persons per week
§ = Based on 4 events or less

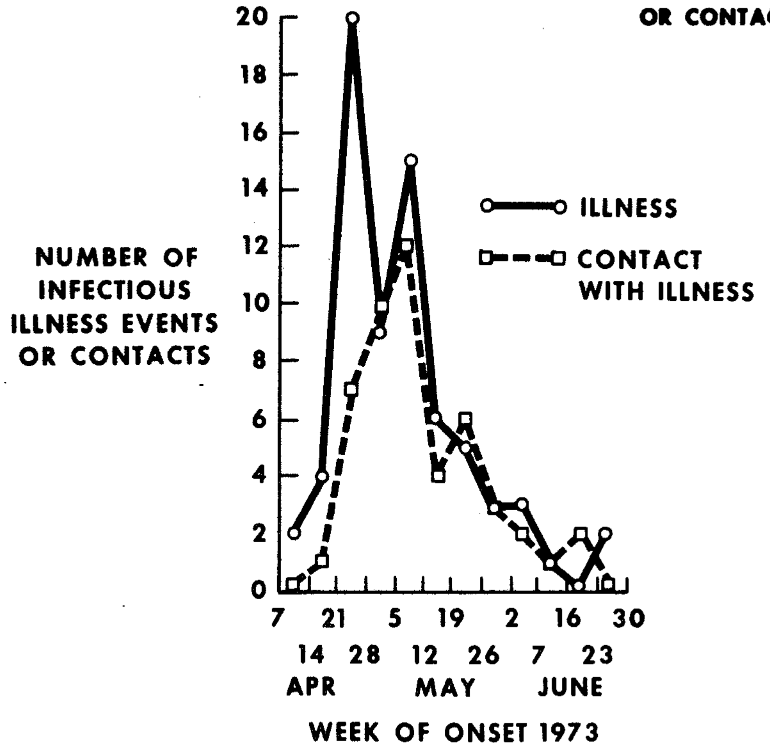
TABLE IX. TYPES OF ILLNESSES WITH WHICH PRIMARY CONTACTS REPORTED CONTACT

Symptom Complex*	Total Reported (All Missions) Number (2 Flights)	Percent of Total (2 Flights)	Percent Reported Per Skylab Mission 2	4
Upper Respiratory Infection	44	60	57	67
Bronchitis	3	4	4	4
Pneumonia	2	3	2	4
Upper Enteric Illness	9	12	10	17
Lower Enteric Illness	9	12	8	21
Fever	8	11	6	21
Headache	7	10	8	13
Skin Infection	9	12	18	0
Other Infectious Illness	4	5	8	0

*One illness contact may contain more than one symptom.

Figures 1 and 2 show plots of weekly reported illnesses and exposure to infectious diseases for Skylab 2 and Skylab 4. Correlation in the reporting of the two events can be observed on both Skylab 2 and Skylab 4. The decreasing rate of reporting contacts parallels the decreasing rate of illness reporting. The pattern of reporting for illness events throughout the Skylab program is illustrated in figure 3. An increased rate of reporting occurred during the preflight and postflight isolation periods. Immediately after launch, reporting decreased and remained low during the missions. Primary contacts responded to the Skylab Flight Crew Health Stabilization Program when it was obvious to them that reporting would be helpful. To the primary contact the most obvious time for reporting was the time when the crewmen were physically present.

A summary of the illness occurrences in the Apollo and Skylab crewmen at mission critical times is presented in table X. A high rate of infection occurred in crewmen from Apollo 7 through Apollo 13 in the absence of a flight crew health stabilization program. The infections included a number of upper respiratory infections, viral gastroenteritis and one rubella exposure. These infections are notably absent with the beginning of the Flight Crew Health Stabilization Program on Appollo 14



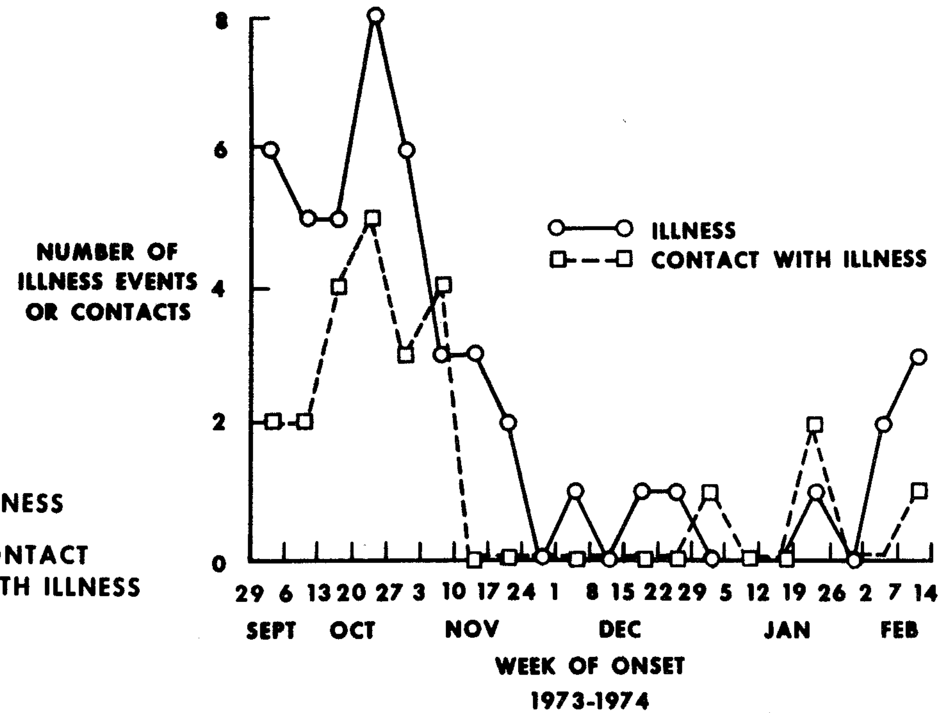


Figure 2. Skylab 4 Flight Crew Health Stabilization Program.

Figure 1. Skylab 2 Flight Crew Health Stabilization Program.

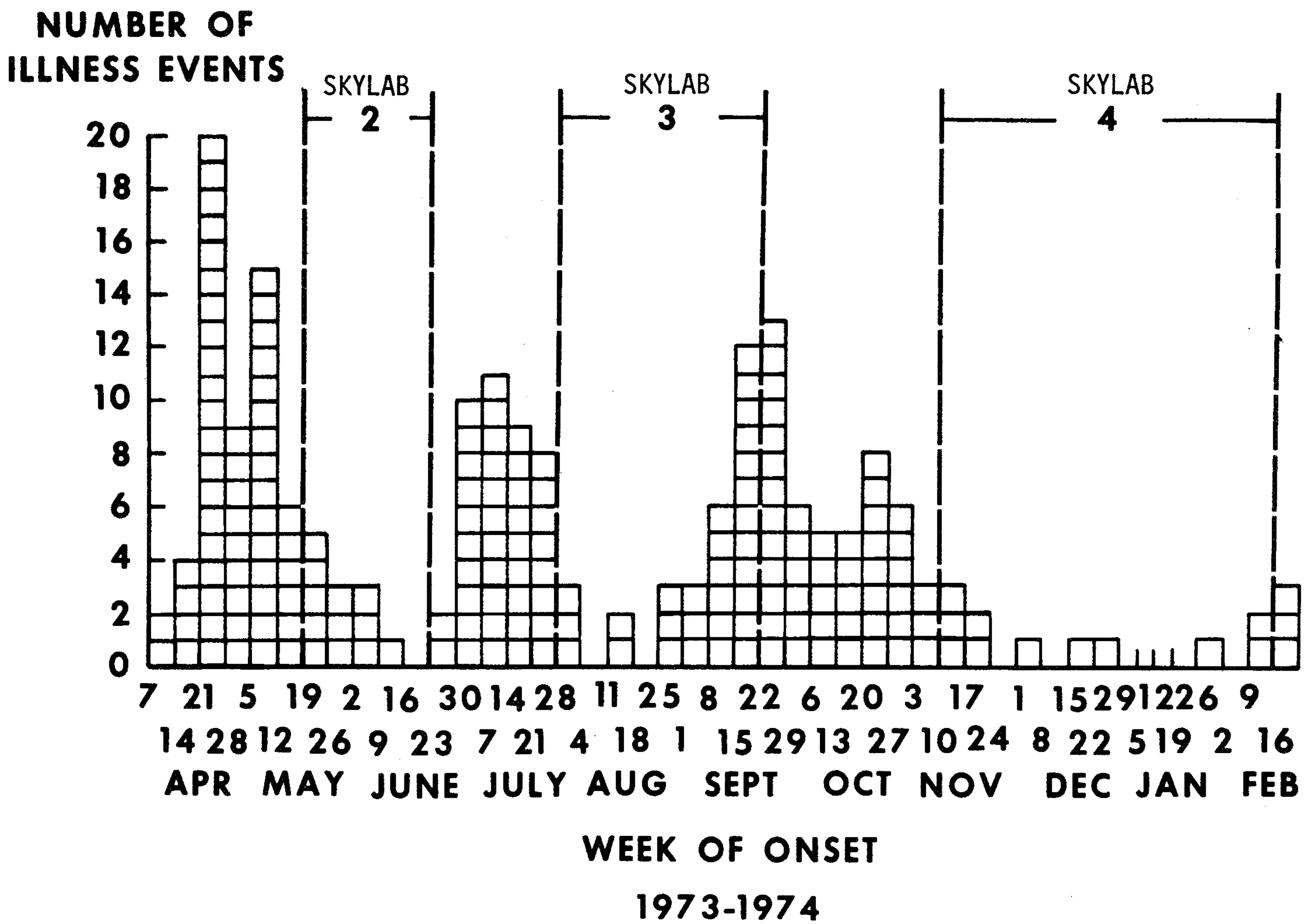


Figure 3. Skylab Flight Crew Health Stabilization Program.

TABLE X. EFFECT OF THE FLIGHT CREW HEALTH STABILIZATION PROGRAM ON THE OCCURRENCE OF ILLNESS IN PRIME CREWMEN

Health Stabilization Program Absent

Mission	Illness Type*	No. Crewmen Involved	Time Period†
Apollo 7	URI	3	M
8	VG	3	P,M
9	URI	3	P
10	URI	2	P
11	-	-	-
12	SI	2	M
13	R	1	P

Health Stabilization Program Operational

Mission	Illness Type*	No. Crewmen Involved	Time Period†
Apollo 14	-	-	-
15	-	-	-
16	-	-	-
17	SI	1	P
Skylab 2	-	-	-
3	SI	2	M
4	SI	2	M

Legend:

Illness Type*:

URI = Upper Respiratory Infection
VG = Viral Gastroenteritis
SI = Skin Infection
R = Rubella Exposure

Time Period†:

M = During Mission
P = Premission

through the Skylab 4 mission. During the missions of Skylab 3 and Skylab 4 a minor skin infection, or rash, occurred on two of the crewmen of each mission. It is doubtful that either of the latter could have been prevented by the measures taken in the health stabilization programs as each problem appears to have occurred for reasons other than preflight exposure. The results indicate that the Flight Crew Health Stabilization Program has successfully accomplished its goal in reducing the number of illness exposures to flight crewmen.

CONCLUSION

The majority of illnesses and contacts to illnesses reported by the primary contacts was the upper respiratory infections. Enteric illnesses represented the next most common illness, but these were relatively rare compared to the upper respiratory infections. The Skylab Flight Crew Health Stabilization Program included a number of preventive measures to reduce the spread of respiratory infections. This emphasis was well placed.

By training primary contacts to report illness and by using a nurse in active surveillance, the Skylab Flight Crew Health Stabilization Program seems to have been effective in reducing the number of infectious illness contacts with the crewmen during the isolation period. The effort made to reduce the number of primary contacts was of greatest importance to the goals of the program. Limiting crew contact to a defined, and medically controlled, population of primary contacts should be continued in future programs. A Flight Crew Health Stabilization Program for future space missions, therefore, should emphasize the initial and continuous training of primary contacts, limited and active sureveillance, specific preventive measures for upper respiratory infections, and the need for concurrent analysis of epidemiological data throughout the program.

Initial Medical Examinations for all Primary Contacts

1. The personnel selected as prospective *primary contacts* will have a medical examination; emphasis will be placed on the detection of infectious disease(s). These examinations will be completed for all *primary contacts* between 60 and 45 days prior to each Skylab flight, and results will be reported on Form 368C by 30 days prior to each flight.

2. The Occupational Medicine Clinics at JSC and KSC will conduct the medical examinations of *primary contacts*.

   (a) The JSC Occupational Medicine Dispensary will support the medical requirements activities for the *primary contacts* located at JSC. The Dispensary will be informed at F-75 days by the Medical Surveillance Office of the names of primary contacts to be examined. This facility will maintain medical records on all *primary contacts*.

   (b) The medical requirements for *primary contacts* at KSC will be supported by the KSC Occupational Health Facility who will be informed at F-75 days by the Medical Surveillance Office of the names of *primary contacts* to be examined.

3. Laboratory Tests for Initial Medical Examinations

   (a) To accomplish all serology and bacterial screening on *primary contacts* in a timely manner, all specimen materials must be collected before or at the time of medical examinations. Basic clinical, routine serological and bacteriological analyses will be accomplished by the JSC Medical Support Laboratories or the KSC Occupational Health Facility. Virological and other serological screening will be accomplished only by the JSC Medical Support Laboratories.

   (b) Laboratory tests will be conducted only on *primary contacts* unless family histories indicate some family members should be checked by laboratory tests. The basic philosophy of testing will be oriented toward screening for subclinical infectious disease. If abnormalities occur in the initial medical evaluation, follow-up testing will be done at the discretion of the examining physician, or Chief, Health Maintenance Branch.

(c) The laboratory tests will include:
Blood. - White cell count with a differential count if WBC is greater than 10 000 or less than 5000.

Urinalysis.

Serology for CRP, SGOT, mumps, rubella, rubeola and RPR (RPR will not be repeated on those who have had this determination as part of their annual physical examination within the previous six-month period).

Throat culture for pathogenic bacteria (food handlers only).

Stool specimen for pathogenic bacteria (for food handlers only).

(d) Specimen requirements for above tests are as follows:
Blood. - 12-ml sample of whole blood
5-ml sample of whole blood for WBC, and differential
7-ml sample of whole blood for RPR, CRP, and serology samples for determining titers for mumps, rubella, and rubeola.

Urine sample.

Throat culture for bacteriology - one, immersed in 2 ml of TSB.

Stool specimen.

Other specimens. - Number and type to be predicated on findings - *i.e.*, at the discretion of the examining physician, or the Chief, Health Maintenance Branch.

(e) Serologic studies to be accomplished by the JSC Virology Laboratory will include screening tests (by HI or NT) for rubeola, rubella and mumps.

(f) Bacteriology examinations performed on *primary contact* food handlers shall include examination for respiratory pathogens (Type A Beta-hemolytic *Streptococcus*, *Staphylococcus*, *Pneumococcus*, *Klebsiella*, and *Haemophilus*). Specimens for phage typing will be sent to JSC for analysis. Microbiology for food handlers will also include feces analysis for bacteriology (*Salmonella*, *Shigella*), ova, and parasites.

(g) Screening for tuberculosis will be accomplished with a yearly PPD (Federal stock No. 6505-105-0102, biologically equivalent to PPD-S).

4. X-ray of the chest - In those individuals with a previously positive skin test for TB, follow-up screening will be done with a chest X-ray only. X-ray will not be repeated on candidates with negative PPD who have had negative chest X-rays within the previous six months.

5. All *primary contacts* must have a current immunization for each required vaccine. Any *primary contact* who is unable, or unwilling to take one or more of the vaccines will be medically disqualified; a waiver may be granted by the Director of Flight Crew Operations or by the Director of Life Sciences for those *primary contacts* considered to be essential to mission operations. The required vaccines are as follows:

Disease	Immunization Required	Immunization Duration
Diphtheria	*	10 years
Tetanus	*	10 years
Influenza	*	4 months
Polio	*	6 years
Mumps	*	5 years
Rubella	*	10 years
Rubeola	*	10 years

*Immunize if no serologic response or history of immunization

6. Physician Review

    (a) The examining physician will review the laboratory analyses, temperature, TB skin test, chest x-ray, and examine the hands, face, neck, scalp, skin, eyes, ears, nose, throat, and feet to determine absence or presence of infectious diseases.

    (b) The examining physician will make a recommendation for medical approval/disapproval on Form 368C and submit the form to the Medical Surveillance Office.

Additional Medical Examinations for Class A *Primary Contacts*

1. Class A *primary contacts* will be reexamined for signs of infectious disease before the F-21 day period for each mission.

    Johnson Space Center and Kennedy Space Center

    (a) All Class A *primary contacts* will be scheduled by the JSC or KSC Clinic for a medical examination from F-28 to F-21 for each mission.

    (b) All food handlers will be reexamined and specimens will be taken at F-21, F-14, and F-7 by the JSC or KSC Clinic personnel for each mission.

2. Laboratory Tests for Additional Medical Examinations

    (a) 5 ml of whole blood for white cell count with a differential count if WBC is greater than 10 000 or less than 5000.

    (b) Urinalysis (for food handlers only).

    (c) Throat culture and stool specimens for pathogenic bacteria (for food handlers only).

    (d) Other specimens. - number and type to be predicated on findings - *i.e.*, at the discretion of the examining physician or the Chief, Health Maintenance Branch.

3. An additional throat examination and temperature determination will be made on Class A *primary contacts* when entering a primary work area.

ILLNESS EVENT FORM
SKYLAB HEALTH STABILIZATION PROGRAM

DATE______________________

NAME____________________________________ SS#______________________

PERMANENT BASE: (circle one) KSC JSC OTHER CONTACT CLASS: A B

ILLNESS_____OR CONTACT TO ILLNESS__________ DATE OF ONSET OR CONTACT__________

CONTACT TO ILLNESS ONLY: NAME OF CONTACT______________________________

AGE__________RELATIONSHIP: HOUSEHOLD OR OTHER (circle)

Description of illness in case or contact: Check appropriate blanks and fill in requested information. This will be used for statistical evaluation.

Duration________________ Symptoms: (describe) ______________________
Temperature_____________ ______________________

Anatomical involvement: (check or answer)

Rhinitis	______	Nausea	______
Otitis media	______	Vomiting	______
Pharyngitis (non-exudative)	______	How frequently?__________	______
Pharyngitis (exudative)	______	Loose stool	______
Cervical adenopathy	______	How frequently?__________	______
Laryngitis	______	Skin rash-pustular	______
Bronchitis	______	Skin rash-Herpes simplex	______
Pneumonia	______	Skin rash-other(describe)	______
Other (describe below)	______	____________________	______
____________________		Headache	______
____________________			

Laboratory studies ordered: (date)

Hematology______________________________
Chemistry______________________________
Bacteriology______________________________
Virology______________________________
Serology______________________________
X-ray______________________________

Return Visits: (Include date, progression of illness, additional signs or symptoms, or date of recovery.) ______________________________
____
____
______________________________Date illness terminated______________

RECOMMENDATION: Return to PC Status__________
Remove from PC Status__________
Date__________________

(Do not write in this blank)

____
Examining Physician

JSC Form 368D (Mar 73) (OT)
Form 4 NASA-JSC

SKYLAB FLIGHT CREW HEALTH STABILIZATION PROGRAM

Operational Definitions of Common Illnesses

Introduction: In order to statistically evaluate the health records generated by the Skylab Health Stabilization Program, we shall record illness episodes by operative definitions. From previous programs, we know that respiratory and enteric illnesses are numerically the most important. Therefore, these illnesses will be described in detail. Other infectious illnesses may be described by diagnosis and duration alone. The information on the illness event form will be coded by an epidemiologist according to the following definitions:

Respiratory Illnesses: Symptoms must last for a period of time greater than 24 hours. Categories are listed by area of involvement.

CODE 1. Upper Respiratory Infection: ear, nose and pharynx signs and symptoms either with or without associated exudative pharyngitis, laryngitis, or cervical adenopathy.

CODE 2. Bronchitis: cough, chest findings of secretions, no evidence of pneumonia.

CODE 3. Pneumonia: infiltrate on chest x-ray.

Enteric Illnesses:

CODE 4. Upper Enteric Illness: nausea and/or vomiting lasting at least two hours.

CODE 5. Lower Enteric Illness: diarrhea - more than three stools of abnormally loose consistency in one 24-hour period, may be associated with upper enteric illness.

Fever: Defined as greater than 99.6° F p.o.

CODE 6. Fever present

Headache: As reported by patient or doctor, either alone or in association with other illness.

CODE 7. Headache present

Skin infection: Any skin eruption determined by a physician to be either infectious or due to an infectious illness.

CODE 8. Skin infection present.

Other infectious illness:

CODE 9. Other infectious illness present.

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SKYLAB ENVIRONMENTAL AND CREW MICROBIOLOGY STUDIES

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ABSTRACT

The results of some ground-based simulations have engendered theories that forecasted microbial "simplification", intercrew transfer of microbial pathogens, autoinfections, and postflight "microbial shock". In an effort to understand the effects of space flight, microbiological samples from multiple sites on the crewmembers were collected several times before, during, and after the space flights. The Skylab data are related to analogous Apollo data and are discussed in a manner that will allow an evaluation of the validity of the hypotheses presented.

Additionally, in-flight environmental samples were acquired from designated sites within the spacecraft and returned to earth for analysis. The resulting data were used to identify potential microbial problems for the maintenance of a habitable environment in the orbital workshop.

INTRODUCTION

The objectives of the Skylab microbiology studies were to detect the presence of potentially pathogenic microorganisms on the crewmembers and their spacecraft and to obtain data which would contribute to an understanding of the response of the crew's microbial flora to the space flight environment. These data were interpreted in light of the

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theories of microbial simplification, intercrew transfer of medically important microorganisms, in-flight autoinfections, and postflight microbial shock, which have been proposed by various authors (1).

Before and after each flight, the twelve areas outlined in table I were sampled from each astronaut. Two calcium alginate swabs, wetted in phosphate buffer, were used to sample the nostrils and each external body surface area. A single, dry alginate swab for virological analyis was used to sample the throat. Phosphate buffer was used to wash the oropharyngeal cavity. Additionally, a midstream urine sample was collected from the first void of the day and fecal specimens were collected at the convenience of the subject. In-flight crew samples, as noted on table I, were collected 16 days before termination of each Skylab mission and returned under chilled conditions for analyses.

Samples were collected before, during, and after each Skylab mission, as shown in figure 1. The Orbital Workshop was sampled up to ten times, including one in-flight sample set. In-flight air samples were collected two days before the end of each mission. The Command Module was sampled on launch and recovery days for each mission. In all cases samples collected in-flight were stored differently, and for a longer time than were preflight and postflight samples. Therefore, direct correlation of the resulting data is not always applicable. The dates and mission designations for all sample collections are illustrated in table II.

In excess of ten thousand selected microbial isolates were analyzed by quantitation, identification, and characterization. Because of the brief time available at this conference to present this quantity of data, the effects of space flight conditions on microbial populations will be examined only to the first level of complexity. That is, only alterations affecting the total autoflora will be evaluated. More detailed analyses conducted at increasing degrees of complexity will be published elsewhere.

RESULTS AND DISCUSSION

Changes in the Habitability of the Skylab Environment

Microbial Content of In-flight Skylab Air

The concentration of bacteria recovered from air samples obtained two days before return from each Skylab visit are displayed in figure 2. Low levels of in-flight bacterial contamination were observed on the first two missions, whereas the recovery from Skylab 4 was considerably

TABLE I. CREW SAMPLE COLLECTION SITES[1]

Sample Designation	Area Sampled
Neck	13 cm^2 below hairline at base of neck
Ears[2]	Right and left external auditory canals with two revolutions of each swab in each ear canal
Axillae	6.5 cm^2 below hair area on each side
Hands	6.5 cm^2 on right and left palms
Navel	The internal area of the umbilicus, and a surrounding 13 cm^2 area with at least two revolutions made with each swab
Groin	5 cm strip from rear to front on right and left inguinal area between legs
Toes[2]	Area between the two smallest toes of each foot
Nares[2]	Both nostrils
Throat Swab[2]	Surfaces of tonsils and posterior pharyngeal vault swabbed with each of two dry calcium alginate swabs
Gargle	60 ml phosphate buffer used as gargle and washed through oral cavity three times
Urine	60 ml midstream sample
Feces	Two samples of 100 mg each taken from center of the fecal specimen

[1]All samples collected before and after each flight.

[2]These samples also collected in-flight 16 days before return from Skylab.

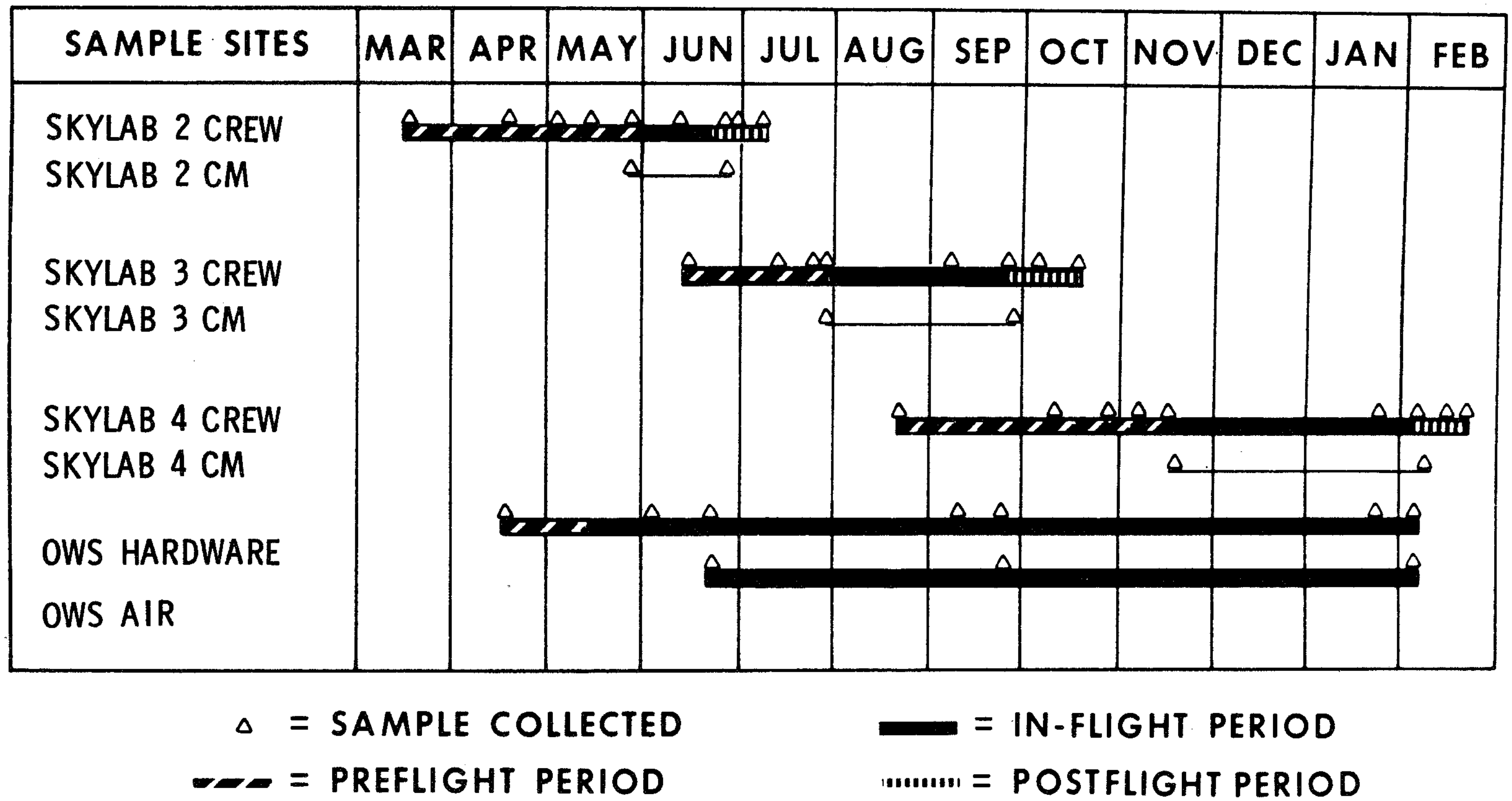

Figure 1. Skylab microbiology sample collection scheme (1973 - 1974).

TABLE II. SKYLAB MICROBIOLOGY SAMPLE COLLECTION SCHEDULE

Sample Type	Collection Period	Skylab 2 Mission Day	Skylab 2 Date	Skylab 3 Mission Day	Skylab 3 Date	Skylab 4 Mission Day	Skylab 4 Date
Crew Samples	Preflight	F-70	3-14-73			F-87	8-21-73
		F-40	4-16-73	F-45	6-13-73	F-35	10-12-73
		F-25	5-1-73	F-14	7-12-73	F-21	10-26-73
		F-15	5-10-73	F-5	7-21-73	F-10	11-6-73
		F-0	5-25-73	F-0	7-28-73	F-0	11-16-73
	In-flight	R-16	6-6-73	R-16	9-9-73	R-16	1-23-74
	Postflight	R+0	6-22-73	R+0	9-25-73	R-0	2-8-74
		R+7	6-29-73	R+7	10-4-73	R+11	2-19-74
		R+18	7-9-73	R+18	10-15-73	R+17	2-25-74
Orbital Workshop Air	In-flight	R-2	6-20-73	R-2	9-23-73	R-2	2-6-74
Orbital Workshop Surface Sites	Preflight	F-40	4-16-73				
	In-flight	R-16	6-6-73	R-16	9-9-73	R-16	1-23-74
		R-2	6-20-73	R-2	9-23-73	R-2	2-6-74
Command Module	Preflight	F-0	5-25-73	F-0	7-28-73	F-0	11-16-73
	Postflight	R+0	6-22-73	R+0	9-25-73	R+0	2-8-74

higher. These higher counts were due entirely to an influx of *Serratia marcescens*, a microorganism which has been shown to produce various infections in man (2). Whereas this species was not recovered from any preflight crew sample analysis, it was recovered from multiple sites from all three Skylab 4 astronauts immediately upon recovery. Further, this species persisted in the nasal cavity of the Pilot throughout the postflight quarantine period. Subsequent investigation demonstrated several potential sources of this organism in the Skylab environment. However, these potential sources could not be sampled in-flight and, therefore, a direct correlation could not be made. By active microbial monitoring the release of this microbial contamination into the Orbital Workshop was traced from possible sources, was detected in the Skylab air, was subsequently recovered as a new species from all three crewmembers, and was ultimately shown to colonize the nasal passages of one astronaut.

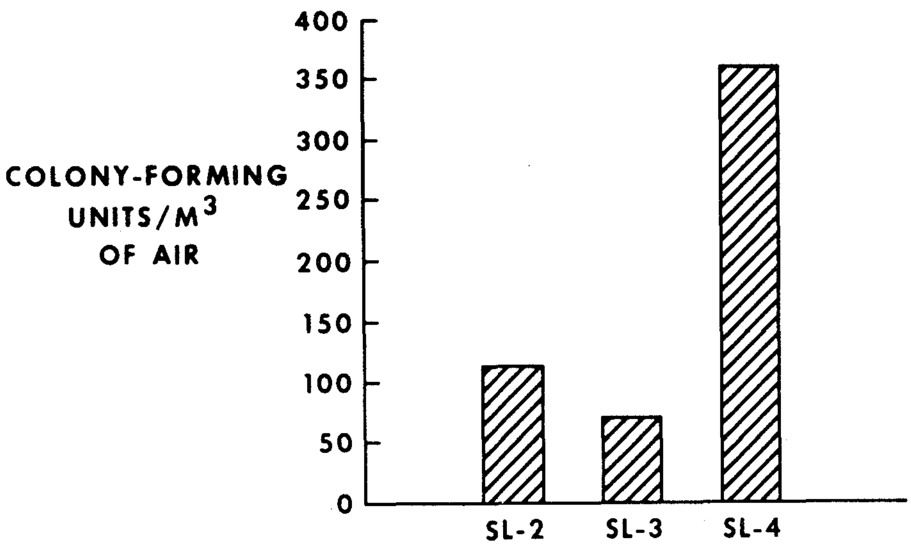

Figure 2. Concentration of bacteria in the Skylab air from samples collected two days before mission termination.

Bacterial Recovery from Sample Sites within the Skylab Orbital Workshop

The total concentrations of viable bacterial cells recovered from the Skylab spacecraft surface sites at various sampling periods are presented in figure 3. These in-flight samples were collected to evaluate the level of microbial contamination occurring in the Orbital Workshop. The results of analysis of samples collected prior to launch are typical of a clean (although obviously not sterile) environment. The

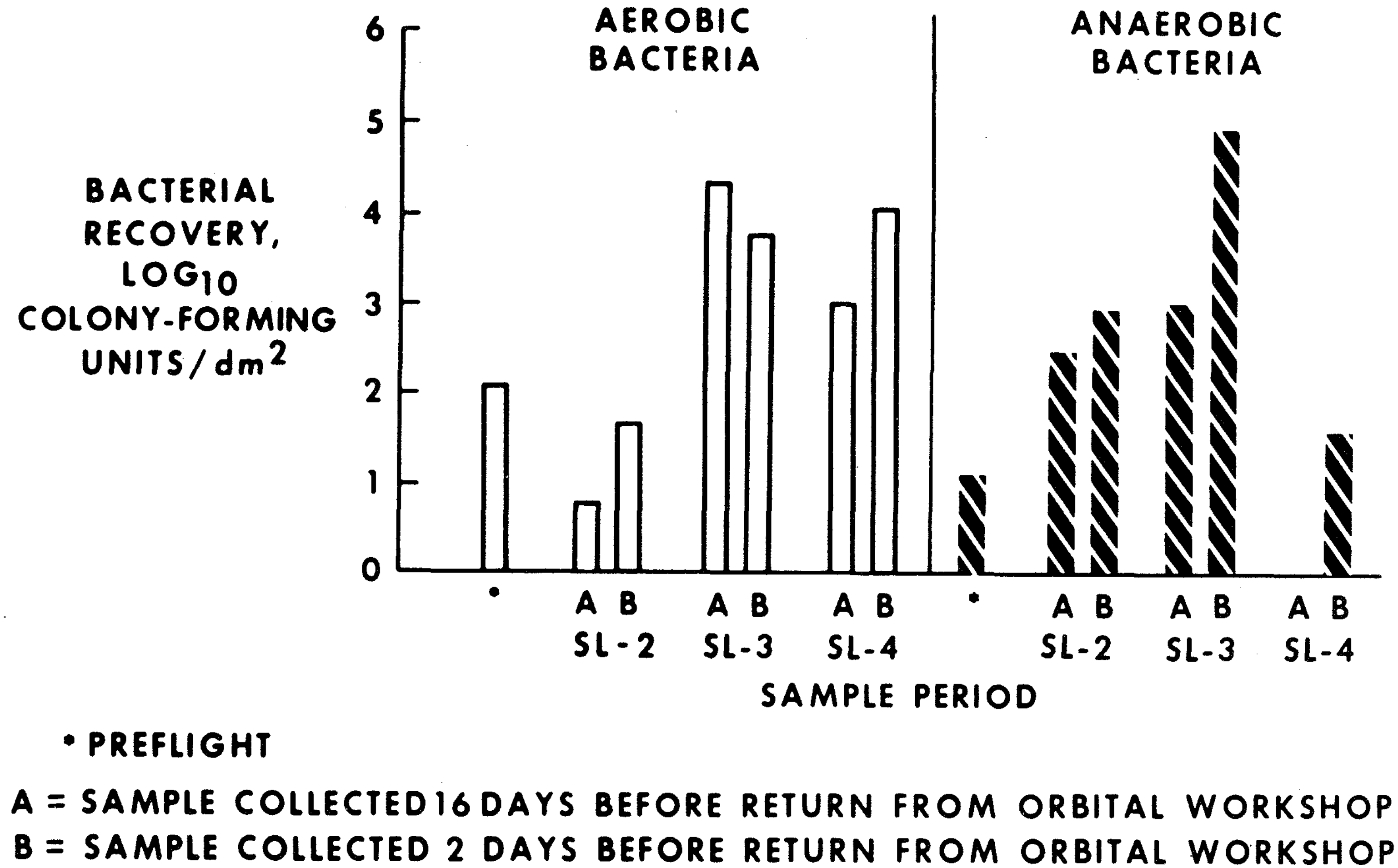

Figure 3. Concentration of bacteria on surfaces in the Skylab spacecraft.

reduction of aerobic bacteria recovered from the Skylab 2 in-flight samples is probably a reflection of the thermal problems experienced in the Orbital Workshop after launch. Although there was a simultaneous ten-fold increase in the presence of anaerobic bacteria, the Skylab 2 crew apparently entered a very clean environment, which remained relatively clean during the mission.

The recovery of both aerobic and anaerobic bacteria from the Skylab 3 mission increased another 1 to 2 $\log_{10}$ units, with no apparent reason except for increased length of habitation by the crewmembers. During the 84-day Skylab 4 mission the total concentration of aerobic bacteria remained nearly constant although anaerobe recovery decreased significantly. This drop was due to the loss of *Propionibacterium acnes* which contributed strongly to the anaerobe population of the other two Skylab missions. This loss of *P. acnes* reflects a similar loss of anaerobic bacteria from the skin surfaces of the astronauts; this datum will be presented later in this paper. This decrease in anaerobic bacterial contamination of the Skylab, therefore, was shown to directly reflect a decrease in these same microbes in the contaminating reservoir, the skin of the astronauts.

The recovery of aerobic bacteria from 15 sites within the Apollo Command Modules, sampled immediately before and after each mission to the Skylab, are summarized in figure 4. Whereas there was some variation in the contamination level of the different Command Modules, there were no major differences between preflight and postflight values for a particular Command Module. Therefore, the variations noted in the Orbital Workshop could not be shown to affect population levels in the Command Modules.

Fungal Recovery from Sample Sites within the Skylab Orbital Workshop

It had been suggested that molds would present problems on long term space flights, especially if high humidities were experienced (3). Figure 5 shows the number of fungal isolations from the Skylab vehicle before launch and during each mission. These numbers were low until the Skylab 4 mission. Although overall humidity was low on the Skylab 4 mission, local areas of high humidity cannot be entire eliminated. The reasons for the large increase in fungal isolations on Skylab 4 have been well established. Early in the Skylab 4 mission, it was discovered that "mildew" was present on the liquid cool garments which had been previously stowed aboard. A sample was taken of this growth, and one liquid cooled garment was returned for additional sampling. In general, the species of fungi isolated from surface samples and air samples were the same species isolated from the liquid cooled garment. These same microorganisms also contaminated the Petri

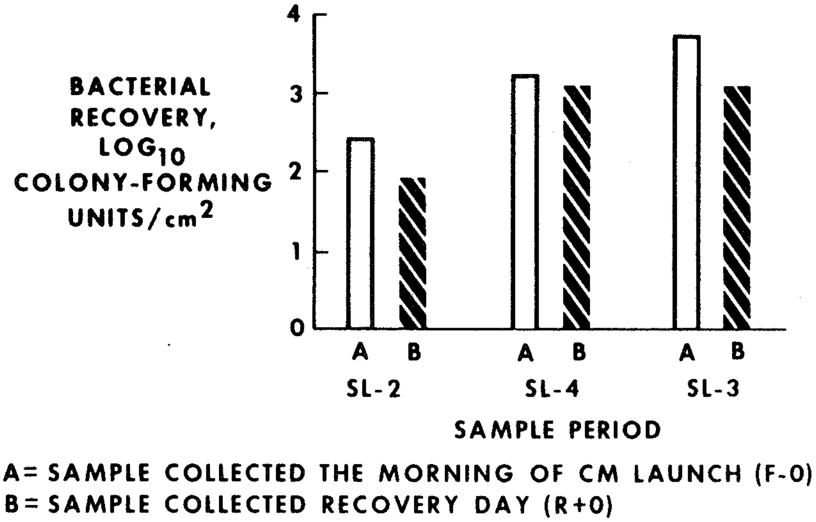

Figure 4. Concentration of aerobic bacteria on surface in the Command Module.

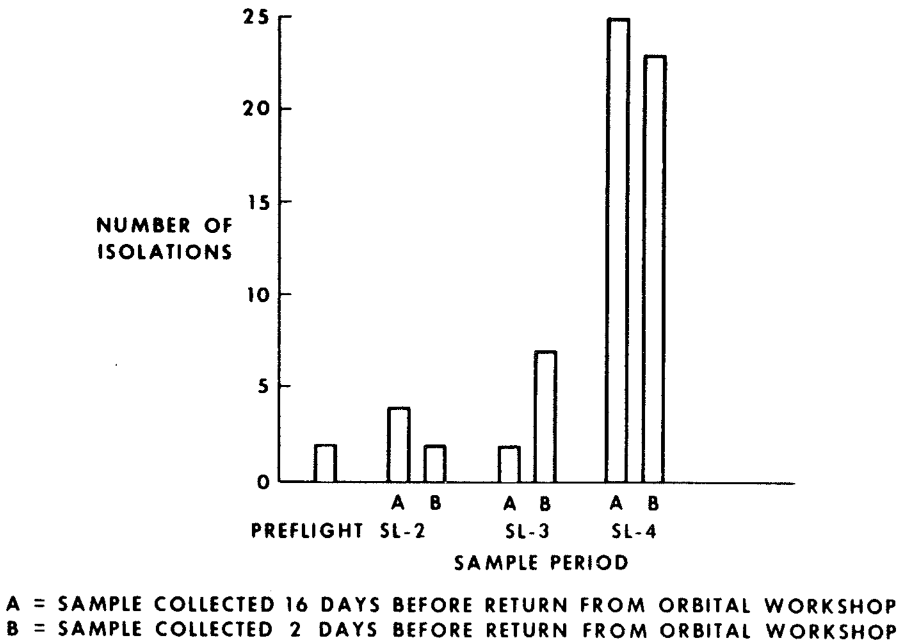

Figure 5. Fungal isolations from surfaces in the Skylab spacecraft.

dishes of the ED31 experiment flown on Skylab 4. It is apparent that the liquid cooled garments were the source of spore contamination since some of these garments had not previously been removed from their original containers, but were subsequently found to be mildewed.

This contamination was also reflected in the recovery of fungi from the crew samples collected 16 days before return from Skylab. For Skylab 2 and Skylab 3 a total of two and zero filamentous fungi, respectively, were isolated from the crew in-flight. On Skylab 4 a total of 11 fungi were isolated, including a significant contamination to the astronauts. It is important to note that this contamination to the crew was demonstrated 62 days after the first exposure to the liquid cooled garments, indicating either continued contamination from inanimate sources, abnormally slow return to normal levels, or both.

The number of fungal species isolated from the 15 Command Module sites before and after each Skylab mission are shown in figure 6. These data illustrate that the fungal contamination of the Orbital Workshop during the Skylab 4 mission did not affect the Command Module samples collected on recovery day. Although the Command Module was attached to the Orbital Workshop during this period of contamination, it was a separate entity, out of the area of heavy use, and away from the contaminating space suits. This relatively clean Command Module probably contributed to the low level of fungal contamination of the crew postflight.

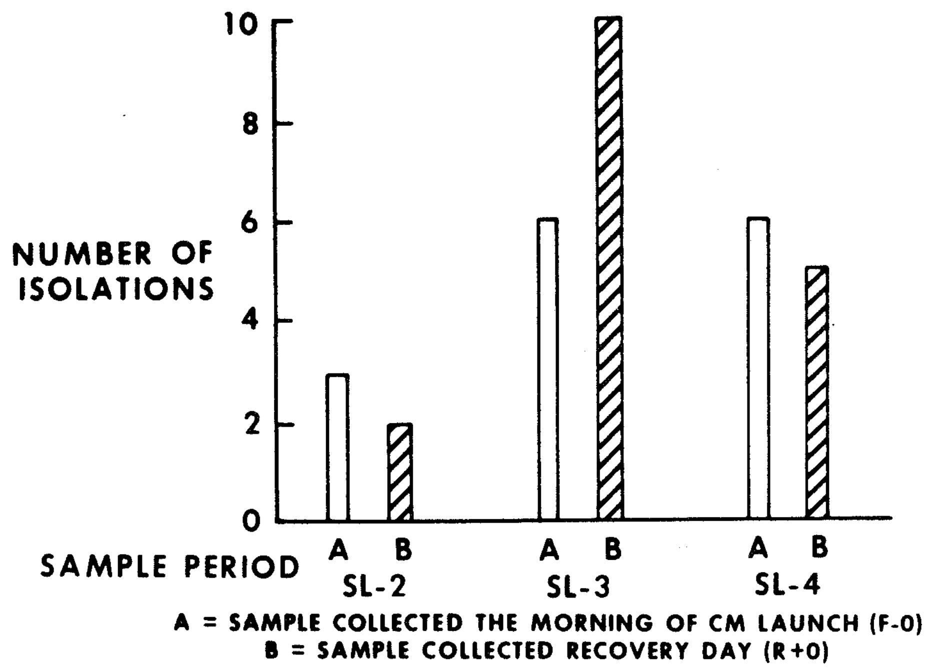

Figure 6. Fungal isolations from surfaces in the Command Module.

Postflight Variation in the Major Components of the Autoflora

Aerobic Bacteria

Prior to the Skylab missions, several authors had theorized that major microflora changes might occur during space flight and that these changes might not be compatible with man's health and welfare on extended missions (4,5,6,7,8,9,10,11,12,13,14,15). The theoretical change which was most often proposed called for a "microbial simplification" which may be defined as a major decrease in the number of different types of microorganisms in the autoflora. To evaluate this hypothesis, the variations of the aerobic bacterial portion of the total autoflora within sample collection sites were analyzed as shown in figure 7. This analysis shows that the frequency with which recovery day values lie outside the preflight range is similar for the 10-day Apollo 14 mission and the three Skylab missions. More specifically, the total number of viable cells recovered was frequently higher postflight whereas the number of genera and species decreased in all missions except Skylab 4. Therefore, it is possible to make the following observations concerning recovery of aerobic bacteria following these space flights. Values obtained from immediate postflight sample analyses are frequently outside of the established preflight range. When different, these values most often reflect an increase in total number of viable cells and a decrease in the number of different genera and species recovered.

Anaerobic Bacteria

A similar analysis of the anaerobic bacterial portion of the total autoflora is shown in figure 8. The analysis presented in this figure illustrates that the anaerobic portion of the autoflora behaves quite differently than the aerobic portion. The frequency and direction of postflight change is different from each Skylab mission, but apparently is not related to mission duration (as the 10-day Apollo 14 and the 84-day Skylab 4 results are most similar). Following the Apollo 14, Skylab 2 and Skylab 4 missions fewer viable anaerobe cells and fewer genera and species were recovered from up to 70 percent of the sites sampled. However, this is not a universal event as all of these values increased in some sample areas following the Skylab 3 mission. These postflight increases were due to an unusually high level of contamination with *Propionibacterium acnes* on the skin of the Skylab 3 astronauts which matched exactly the increased contamination of Skylab surfaces mentioned earlier.

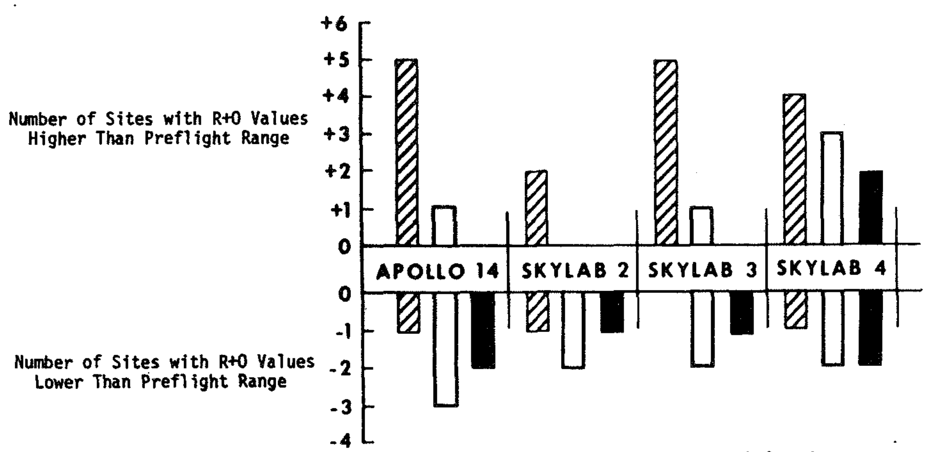

Figure 7. Postflight change in aerobic bacteria.

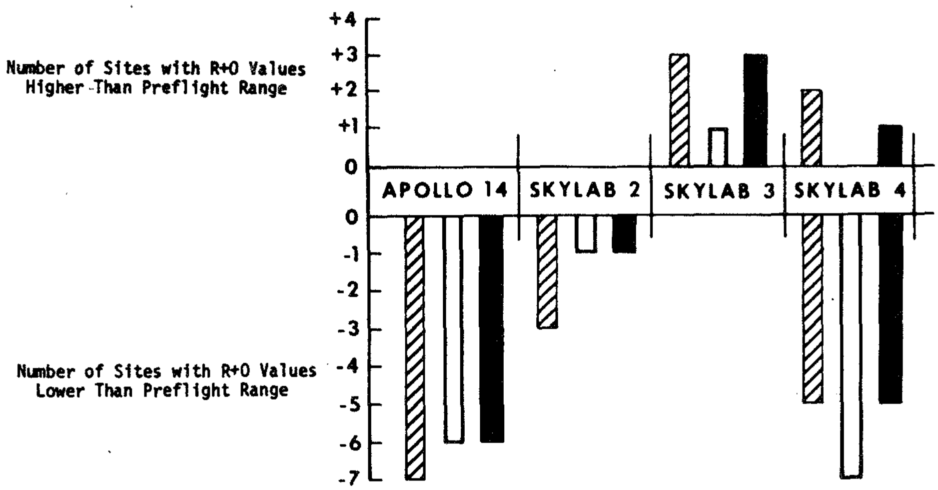

Figure 8. Postflight change in anaerobic bacteria.

Legend

Bars above the line indicate the number of the areas tested for which values were obtained that were higher than the preflight range. Bars below the line indicate the number of areas with decreased values postflight (R+0). All values represent the mean of 3 astronauts. Ten sites were sampled from each astronaut.

▨ Total Count of Viable Cells

□ Number of Different Genera

■ Number of Different Species

The summaries presented in figures 7 and 8 indicate that, whereas the trends are not inviolate, the following conclusions may be stated. Gross numerical changes in the autoflora cannot be correlated with mission duration up to 84 days. Total numbers of viable bacterial cells tend to increase for aerobes and decrease for anaerobes. The number of different aerobic genera and species change little, whereas there is generally a decrease in the number of different anaerobic types recovered.

Yeasts and Filamentous Fungi

We have previously shown, as demonstrated in figure 9, that for the Apollo missions there was, typically, a significant reduction in the number of isolated fungal species up to the launch day. This was taken to be indicative of severely restricting opportunities of contamination to the crew for three weeks before flight. Analysis of postflight Apollo data indicated that exposure to the space flight environment for up to two weeks resulted in an even greater reduction with a relative increase in incidence of the potential pathogen, *Candida albicans* (16).

Essentially the same pattern may be demonstrated from the Skylab 2 and Skylab 3 data, as shown in figures 10 and 11. However, fungal recovery was not depressed following the 59-day mission of Skylab 3, indicating increased exposure to fungi within the Skylab. Results of the same analyses for Skylab 4 are shown in figure 12 where essentially the same pattern is again demonstrated. This is an important observation in light of the previously mentioned in-flight contamination of the Orbital Workshop and Skylab 4 crew and the fact that the Skylab 4 Pilot sustained a "rash" in-flight which was presumed to be a mycotic infection and responded to treatment with Tinactin®. In spite of the gross contamination, the probable mycotic infection, and the epic length of the space flight, approximately the same number of fungal isolates were recovered from the Skylab 4 crewmembers throughout the 17-day postflight quarantine period. This indicates that with adequate preparation, monitoring, and treatment (if necessary) it is possible to control mycological problems in space for missions of this length where the humidity is generally low.

Behavior of Medically Important Components of the Autoflora

Opportunity for Postflight Microbial Shock

A summary of the numerical means of recovered isolates of medically important microorganisms from all nine prime Skylab crewmembers is presented in figure 13. This summary indicates that the incidence of

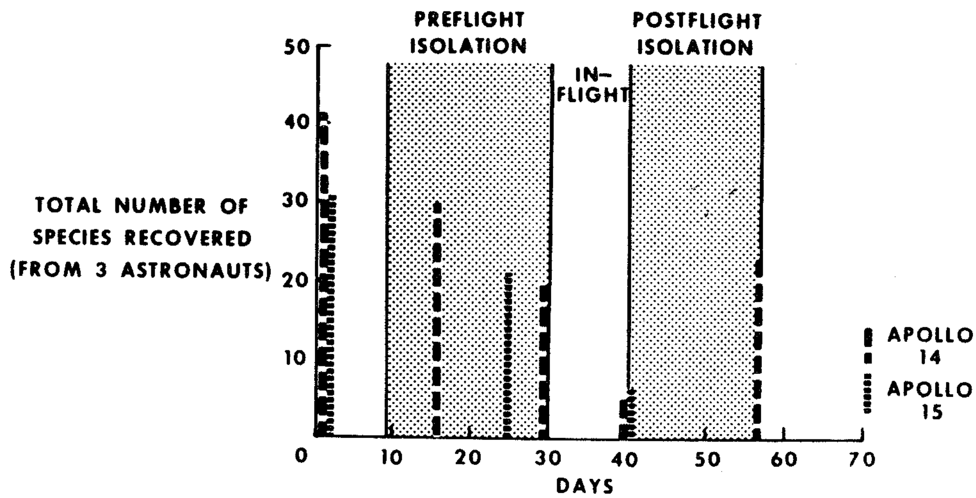

Figure 9. Total number of fungal species recovered from each set of Apollo 14 and 15 crew samples (21).

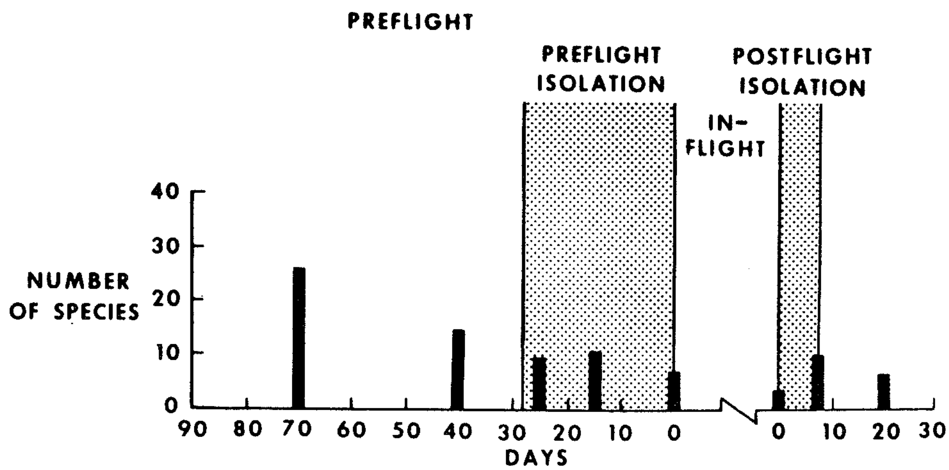

Figure 10. Total number of fungal species recovered from each set of Skylab 2 crew samples.

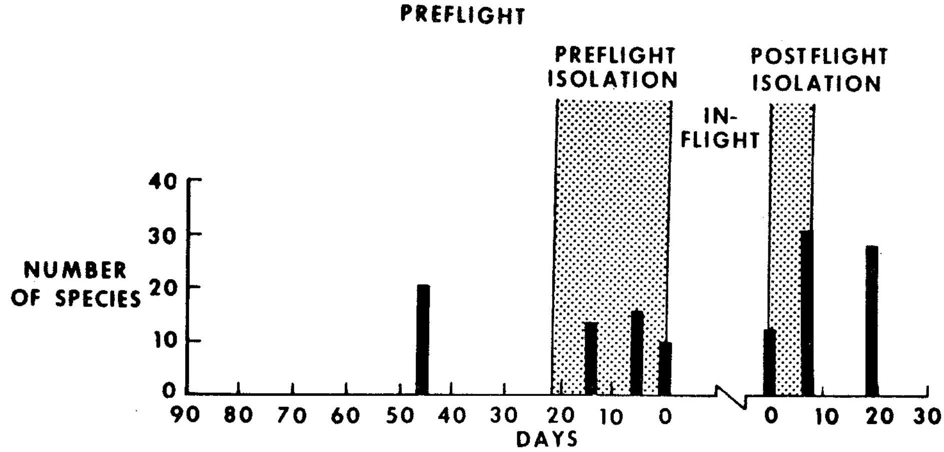

Figure 11. Total number of fungal species recovered from each set of Skylab 3 crew samples.

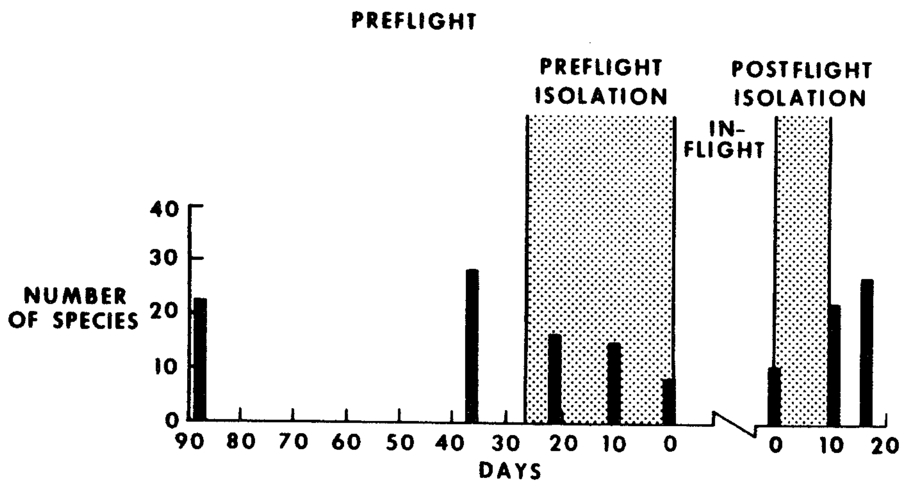

Figure 12. Total number of fungal species recovered from each set of Skylab 4 crew samples.

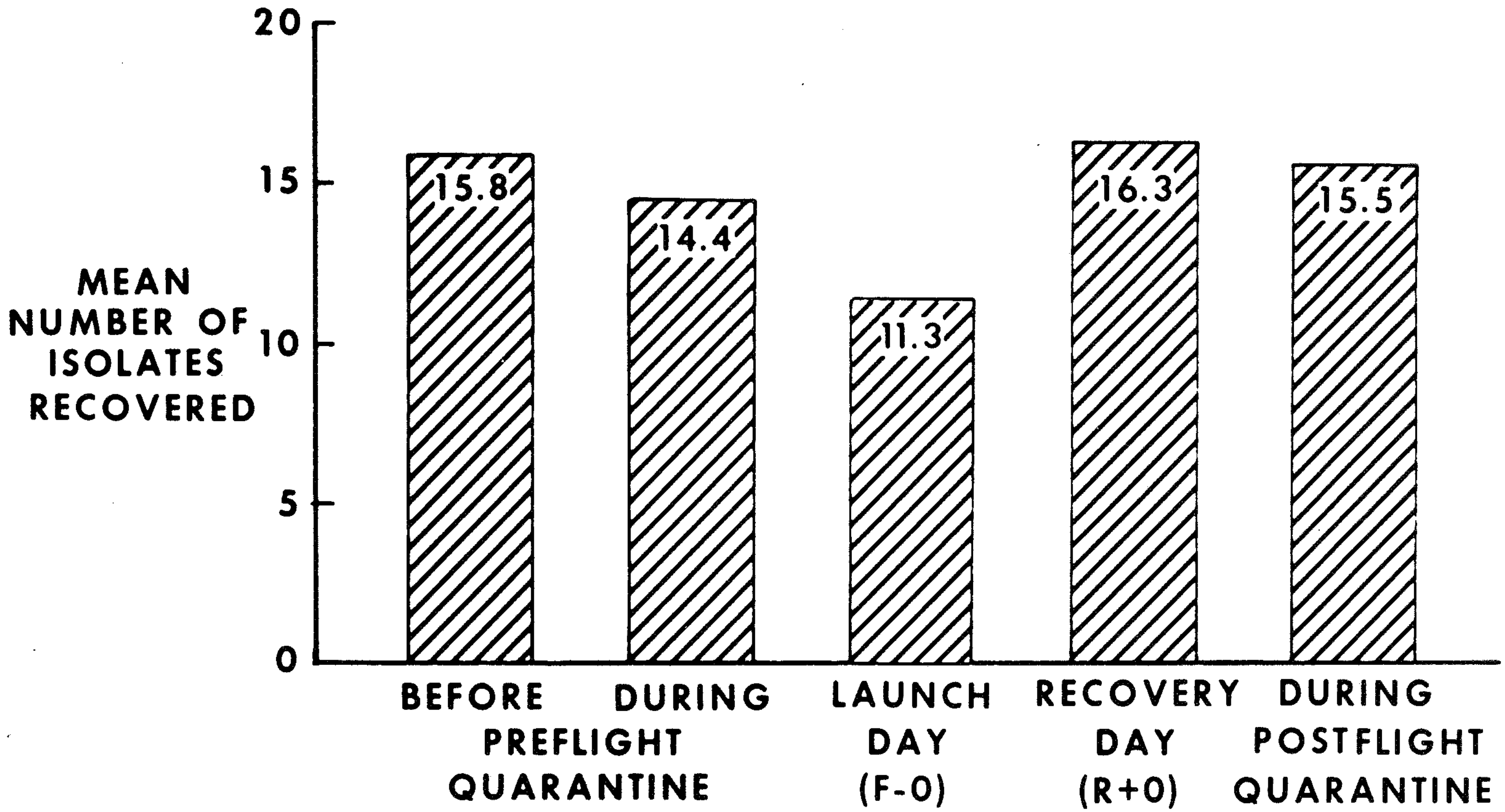

Figure 13. Mean of combined incidence of recovery of medically important bacteria from all three Skylab missions.

these species on the body decreased during the preflight quarantine period, to establish a low point the morning of launch. This event no doubt reflects decreased contact with these species during this quarantine period. The largest number of medically important microorganisms is recovered from the immediate postflight sample set after which the value returns to its near normal prequarantine value.

Several authors have warned that returning space travelers may experience a "Microbial Shock" and may respond negatively to renewed contact with potentially pathogenic microorganisms which are absent in the space flight environment (7,12,17,18,19,20).

This warning is based on the assumption that contact with potential pathogens during space flight would be very limited, resulting in a reduction of immunocompetence. However, these data show that there is an increase in the distribution of potential pathogens immediately following space flight. This result supports earlier findings reported for shorter duration space flights (14,17,21,22,23). Therefore, if a reduction in total immunocompetence were to occur during these missions, it is difficult to see how this reduction would be in response to decreased contact with medically important components of the autoflora. As with the Apollo missions, there was no clinical or microbiological evidence of any "Microbial Shock" following any of the Skylab missions.

Intercrew Transfer of Potentially Pathogenic Microorganisms

Transfer of pathogenic microorganisms between crewmembers during space flight has previously been reported for missions up to 18 days (24,17, 21,22). During the Skylab series it was possible to demonstrate in-flight cross-contamination, colonization, and in-flight infection with *Staphylococcus aureus*. Most strains of this species, which is one of the most infectious of the common inhabitants of man's autoflora, may be distinguished by their reaction with specific bacteriophages. This allows us to monitor the exchange of these microbes with greater resolution. The phage-type pattern of *S. aureus* recovery for Skylab 2 is shown on table III. These data show that the same *S. aureus* phage type was repeatedly recovered from the nasal passages of the Pilot, indicating that this crewmember was a carrier of this microorganism. Although spread to the Oribtal Workshop was demonstrated, there was apparently no transfer to the other crewmembers in-flight. Therefore, being restricted to a confined space for 28 days with an *S. aureus* carrier does not necessarily result in cross infection.

TABLE III. *Staphylococcus aureus* RECOVERED DURING SKYLAB 2 MISSION

Sample Period (Days)	Commander		Scientist Pilot		Pilot		Orbital Workshop	
	Sample Site	Phage Type	Sample Site	Phage Type	Sample Site	Phage Type	Number Of Sites	Phage Type
Preflight								
-70	-	-	-	-	NASAL	52		
-40	-	-	-	-	NASAL	N.T.*		
					URINE	80		
-25	NAVEL	N.T.	-	-	NASAL	N.T.		
-15	-	-	-	-	NASAL	6/80		
-0	-	-	-	-	NASAL	80		
					GARGLE	80		
					SCALP	80		
In-flight	-	-	-	-	NASAL	80	1	N.T.
					NASAL	52/80	1	80
Recovery								
+0	-	-	-	-	NAVEL	52/80		
+7	-	-	-	-	-	-		
+18	-	-	-	-	NASAL	80		
					GARGLE	52/80		
					NAVEL	52/80		

*N.T. = Non Typable

A more complex situation is outlined on table IV. The data summarized in this table indicate that the Skylab 3 Commander and Pilot were both nasal carriers of *S. aureus*, carrying phage type 3A and 29/79, respectively. Prior to the flight, *S. aureus* was not recovered from any of the Scientist Pilot samples. Analyses of in-flight-collected samples show that the workshop became contaminated with both phage types and that type 29/79 was temporarily transferred to the Scientist Pilot. Postflight analyses show that type 3A had spread to the Pilot but, as could be expected (25), did not colonize this subject who was already a carrier of another phage type. Phage type 3A was repeatedly isolated from the postflight specimens of the Scientist Pilot, indicating actual colonization. This is a clear demonstration of in-flight intercrew transfer of a pathogenic species where the contaminant could be shown to have established itself as a member of the autoflora of the new host.

It is important at this point to relate these observations to crew in-flight illness events during the Skylab 3 mission. The Pilot, a 29/79 carrier, developed a hordeolum (sty) which was successfully treated with Neosporin®. The Commander, a 3A carrier, developed axillary swellings of a furuncle (boil) type which were treated with warm compresses. As neither of these infections were draining, in-flight contingency samples were not taken, so we do not know for sure the identity of the causative agent. However, we do know that the causative agent of both of these maladies is usually *S. aureus*, and both of these individuals were carriers of this microorganism. Therefore, it is accurate to say that we have traced the development of a pathogenic microorganism from its preflight carrier state in two crewmembers through in-flight contamination of the Orbital Workshop, and colonization on the third crewmember. Also, it is highly probable that this species was responsible for the active in-flight infections of the two *S. aureus* carriers.

CONCLUSIONS

A general overview of some of the general contamination of the Skylab vehicle and of the major activities of the microbial autoflora of the Skylab astronauts has been presented. These data show that, while gross contamination of the Skylab environment was demonstrated and there were several in-flight disease events (presumably of microbial origin), such events were not shown to be limiting hazards for long-term space flight. Evaluation of the major groups of microorganisms, comprising the microbial populations tested, tended to support the theory of microbial simplification for anaerobic bacteria, but not for other microbes. Intercrew transfer of pathogens was demonstrated. The

Table IV. *Staphylococcus aureus* RECOVERED DURING THE SKYLAB 3 MISSION

Sample Period (Days)	Commander		Scientist Pilot		Pilot		Orbital Workshop	
	Sample Site	Phage Type	Sample Site	Phage Type	Sample Site	Phage Type	Number Of Sites	Phage Type
Preflight								
-45	NASAL	3A	-	-	NASAL	29/79		
					2 Skin Sites	29/79		
-14	NASAL	3A	-	-	NASAL	29/79		
	4 Skin Sites	3A						
-5	NASAL	3A	-	-	NASAL	29/79		
-0	NASAL	3A	-	-	-	-		
In-flight	NASAL	3A	NASAL	29/79	1 Skin Site	N.T.*	6 Sites	3A
							2 Sites	29/79
Recovery								
+0	NASAL	3A	NASAL	3A	NASAL	29/79		
	1 Skin Site	3A	GARGLE	3A	GARGLE	29/79		
					1 Skin Site	29/79		
					1 Skin Site	3A		
+7	NASAL	3A	NASAL	3A	-	-		
	3 Skin Sites	3A						
+18	NASAL	3A	NASAL	3A	NASAL	29/79		
	GARGLE	3A						
	2 Skin Sites	3A						

*N.T. = Non Typable

data mediate against the theory of postflight microbial shock. The question of in-flight autoinfection remains unanswered because none of the in-flight disease events were evaluated microbiologically.

Further general evaluations of the dynamics of the autoflora as a whole, and specific analyses of selected species and groups, will be published separately.

ACKNOWLEDGMENTS

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RADIOLOGICAL PROTECTION AND MEDICAL DOSIMETRY FOR THE SKYLAB CREWMEN

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*R. A. English, Ph. D.**

ABSTRACT

Dose equivalent radiation exposure of the Skylab crewmen has been maintained well below the limits recommended by the Radiobiological Advisory Panel, Committee on Space Medicine, National Academy of Sciences. Operational procedures and mission rules were established; ground support specialists were responsible for overall coordination and evaluation of data from Skylab onboard radiation-monitoring instruments, satellite monitoring systems, and solar observatory reports. Also, the Skylab crewmen were provided with instrumentation and training to enable autonomous response had a radiation problem arisen while the spacecraft was not within range of a ground communications site. A comparison among all Skylab crewmen of dose equivalents to skin, lens of the eye, and blood-forming organs is presented in this paper.

INTRODUCTION

Radiological protection planning for the Skylab missions encompassed two major areas; those radiation exposures that were "expected" whose components were known with relative certainty and those radiation exposures that were "unexpected" or completely indeterminant. The expected radiation components were the trapped protons and electrons of the Van Allen Belts (figure 1), galactic cosmic rays and the emissions of onboard sources (table 1). The possibilities of unexpected exposure include energetic solar particle events, high altitude nuclear tests, and potential problems with onboard sources.

Premission analyses indicated that dose equivalents from the nominal environment of trapped (Van Allen belt) particles and galactic cosmic radiations would be well below the limits adopted by National Aeronautics and Space Administration from the National Academy of Sciences recommendations for manned space flight (table II) (1). These analyses indicated that the Skylab 2 mission (28-day duration) would be

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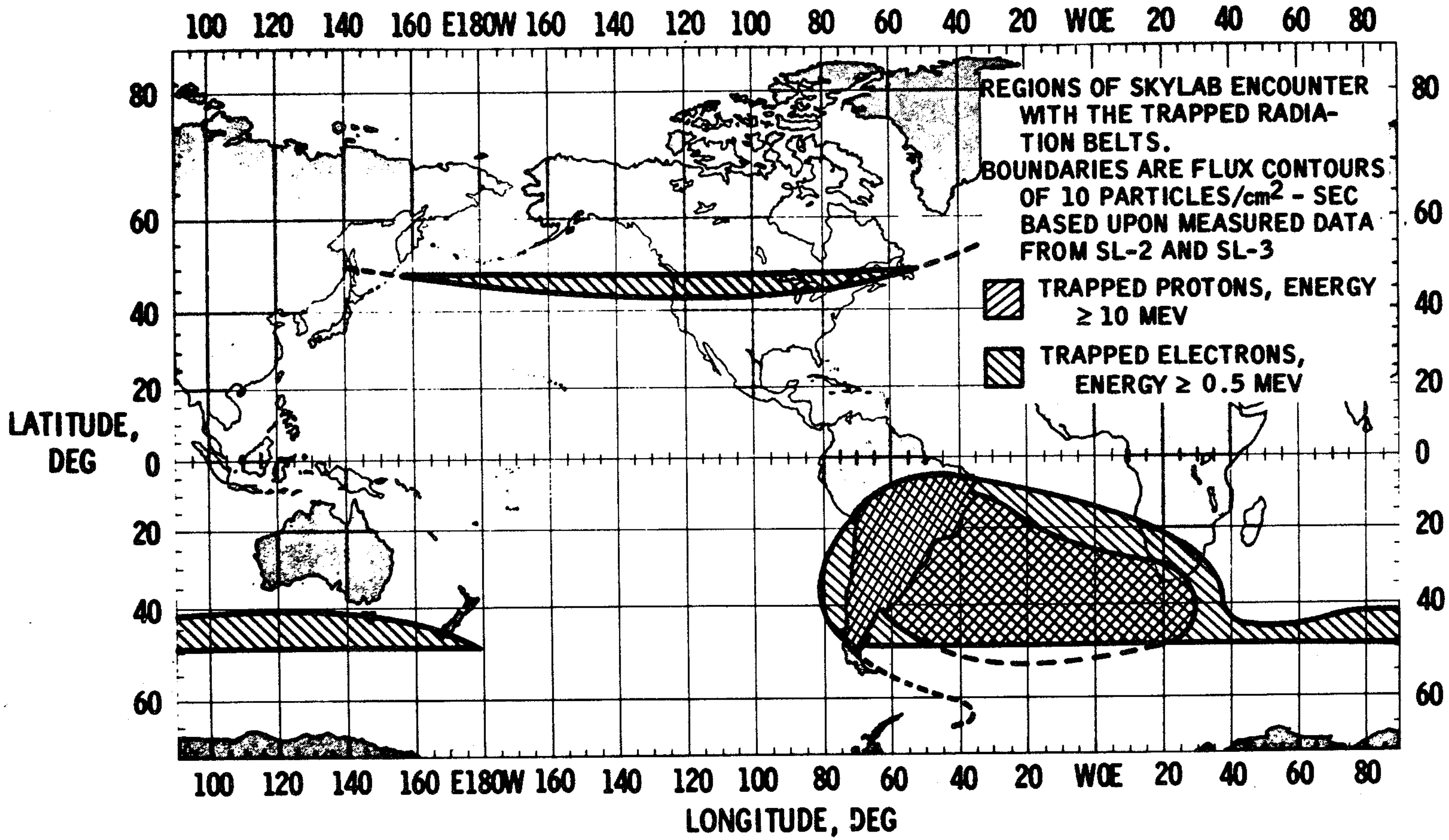

Figure 1. Trapped radiation environment boundary for Skylab.

TABLE I. RADIATION SOURCES ABOARD THE SKYLAB VEHICLE

ITEM IDENTIFICATION	LOCATION	SOURCE MATERIAL	ACTIVITY PER ITEM	NOS. ITEMS	TOTAL
Photometer Calibration Source Experiment T027	Forward Compartment	Pm-147	8 mCi	1	8 mCi
Light Source for Otolith Goggles Experiment M131	Experiment Compartment	H-3	100 mCi	2	200 mCi
Dial Lettering Experiment S019	Forward Compartment	Pm-147	NA	NA	200 mCi
M552 Ampoules	Stowage Compartment	Ag-110m	20 μCi	4	80 μCi
M558 Ampoules	Stowage Compartment	Zn-65	13 μCi	3	39 μCi
Docking Target Axial	External On the MDA	Pm-147	300 mCi	66	19.8 Ci
Docking Target Radial	External On the MDA	Pm-147	300 mCi	66	19.8 Ci
CO_2 Partial Pressure Sensors	Internal On AM	Am-241	454.2 μCi	12	5.5 mCi
G&N Main Frame (PSA & CDU)	Command Module	Th-232	NA	NA	34.1 μCi
Astronaut Chronographs	Worn	H-3	4.21 mCi	3	12.6 mCi

Key: mCi = millicurie NA = not applicable
μCi = microcurie MDA = Multiple Docking Assembly

TABLE II. RADIATION EXPOSURE LIMITS

CONSTRAINTS IN rem	BONE (5 cm)	SKIN (0.1 mm)	EYE (3 mm)
1 yr avg Daily Rate	0.2	0.5	0.3
30 Day max	25	75	37
Quarterly max	35	105	52
Yearly max	75	225	112
Career Limit	400	1200	600

within the 30-day limit category, while Skylab 3 and 4 (59 days and 84 days, respectively) would be within the 90-day category. Because the nominal environment would result in doses well below these limits, operational radiation support was geared toward rapid identification and reaction to any enhanced radiation situation.

SPACECRAFT RADIATION MONITORING

The communications network for the Skylab missions could not provide continuous communications between the spacecraft and the ground. The existence of relatively large communication gaps necessitated providing the astronauts with instrumentation and training to insure that the crews could act autonomously to limit radiation exposure in a contingency situation. Mission rules establishing mandatory onboard decisions were written only for the relatively radiation sensitive intervals of extravehicular activity.

The onboard instruments available for crew readout included a portable rate survey meter and three (plus a spare) personal radiation dosimeters which display integrated dose in 10 millirad integrals. The personal radiation dosimeters and rate survey meter provided the dual functions of extravehicular activity dosimetry and dose rate monitoring, plus vehicle area monitoring in the intervals between extravehicular activities.

Routine monitoring of dose rates at a fixed loaction aboard the Skylab vehicle was performed by an ionization chamber instrument, the Van Allen Belt Dosimeter. Electron and proton fluences (particles/cm^2) were monitored by an electron-proton spectrometer mounted on the exterior of the spacecraft. Rate data from these instruments were telemetered or recorded for later transmission to ground, and were not available for direct crew readout.

PASSIVE DOSIMETRY

Each crewman was provided with a passive dosimeter packet to be worn continuously throughout the mission. The packet weighed approximately one-half ounce, and was designed to be worn on a soft strap on the ankle or wrist. The packet contained the following dosimetry materials for postflight analysis: densitometric film, nuclear track emulsions, polycarbonate and cellulose nitrate track detectors, lithium fluoride (TLD-700) chips, and tantalum/iridium foils.

In addition to passive dosimeters worn by the crewmen, passive dosimeters were placed within the orbital workshop's film storage vault

for the intervals from the beginning of Skylab 2 to the end of Skylab 2 (28 days) and from the beginning of Skylab 2 to the end of Skylab 3 (123 days). The film vault dosimeters were placed in locations with approximate 2π shielding values of 13 and 23 g/cm^2 aluminum.* Relative to proton range in tissue, these depths in aluminum correspond to soft tissue depths of approximately 10 and 19 cm, respectively.

GROUND RADIATION MONITORING

Radiation protection support was provided by specialists in communications, computational analysis, and radiological health. Spacecraft data, satellite information and solar observatory reports were utilized in evaluating the space environment, especially relative to radiation enhancement. The crewmen reported their personal radiation dosimeter readings (as integrated dose) on a daily basis, plus additional readings before and after each extravehicular activity. These readouts confirmed a continuously nominal radiation environment throughout each of the three missions.

Although there were no radiation enhancements, the mission was not totally uneventful from a radiation standpoint. A few highlights are as follows.

Solar Activity

The Skylab missions were flown during a period when solar activity was approaching a minimum in the sun's solar cycle. Nevertheless several events of scientific interest occurred during the Skylab missions, however, particle emissions from these events were of low energy and relatively low intensity. These characteristics, coupled with the shielding effect of the Earth's magnetic field, reduced radiation doses from solar particles to below the limits of detectability for onboard dosimetry instrumentation (< 10 millirad per event).

Nuclear Events

A series of four nuclear devices were detonated by France at their Murora Test Site during Skylab 3. The tests produced no ionizing radiation problems for Skylab. However, we did recognize the possibility of eye damage to the crew from accidental observation of a test. This situation was handled by completely avoiding any visual observation of ground sites in the vicinity of the test area.

*Due to the rectangular shape of the film vault, actual 2π mean values are somewhat greater than 13 and 23 g/cm^2. The remaining 2π shielding is $\geq$ 23 g/cm^2 for both locations.

Onboard Radiation Source Problems

One of the larger onboard sources (approximately 200 millicuries of promethium-147) was in the form of radioluminescent markings on knobs and dials of an experimental device, the Experiment S019 "Articulated Mirror System". Roughly half of the total activity was applied to digital readout belts and wheels within a readout subassembly. Two malfunctions occurred with the device in flight. First, a number of radioluminescent numerals ($\approx$ 1 mCi each) became detached from one of the dial wheels, and second (perhaps because of the first), a belt of numerals became jammed and failed to indicate instrument position in the 10's and 100's places of rotational attitude.

The possibility of numeral detachment had been recognized late in the preflight preparations for the missions and the dial subassembly had been gasket-sealed to preclude escape of promethium-147 into the spacecraft atmosphere. The problem during the flight became one of how to obtain valid experimental results, either by fixing the jammed belt (without release of promethium-147) or by finding an alternative alignment method for the experiment. Ground based testing with a training model of the experiment equipment determined that the numeral belt could not be freed without breaking into the sealed dial unit. In the meantime, an alternative alignment method was devised and tested. The alternative method was successful and was utilized for the remainder of the mission.

DOSIMETRY RESULTS

Integrated radiation doses at a shield depth equivalent to lens of the eye were obtained daily by crew readout of personal radiation dosimeters. These dosimeters were worn the first four days of each mission and for all extravehicular activities. During the rest of each mission, the instruments were placed in the designated assigned positions shown in table III. Mean dose rates for similar positions in consecutive missions show a trend toward increased values as use of food, water, propellants and other expendables reduced the overall spacecraft shielding. Thermoluminescent dosimeter results for the crew worn passive packets are shown in table III for comparison with the rates found throughout the spacecraft.

An upper limit estimate of the hard galactic radiation contribution is approximately 18 millirad per day; the approximate lower limit is 12 millirad per day. Comparison of these rates with the overall mean dose rates shown in table III indicates that the galactic component accounted for 30 to 50 percent of the observed film vault doses, and roughly 20 to 30 percent of the crew dose means.

TABLE III. MEAN DAILY DOSES WITHIN SKYLAB VEHICLE

LOCATION	SKYLAB MISSIONS (rad/day) 2	3	4
Crew TLD (Mean ± σ)	0.057 ± 0.003	0.065 ± 0.005	0.086 ± 0.009
Film Vault, Drawer B	0.041	0.038	-------
Film Vault, Drawer F	0.037	0.030	-------
Command Mod., B-1	0.080	0.073 0.085 *	0.084
Stowed Crew PRD's			
Experiment Comp	0.054	0.047	0.070
Sleep Compartment	0.083	0.082	0.091
-Z SCI Airlock	0.071	0.110	------
+Z SCI Airlock	------	------	0.126
Mean, Outside Vault ± σ	0.069 ± 0.013	0.077 ± 0.021	0.091 ± 0.021

Legend:

* A constant, dose independent, integration rate (0.012 rad/day) was observed in this instrument postflight. If initiated at launch, true in-flight rate would be 0.073 rad/day; if initiated at splashdown, rate of 0.085 rad/day would be valid.

TLD = Thermoluminescent Dosimeters

PRD = Personal Radiation Dosimeters

The majority of the remaining dose originates from protons of the Van Allen Belts and softer secondary radiations generated by passage of the primary particles through spacecraft materials.

The evaluation of dose equivalents for mixed radiations in space is a complex subject and it is recommended that the reader consult the literature for rigorous discussion on this subject. There are, however, some notable findings which should be covered.

Primary Electrons

Van Allen belt electrons did not penetrate into the spacecraft, nor were they found to penetrate deeply enough (3 mm tissue equivalent) during extravehicular activities to register on either the passive dosimeters or personal radiation dosimeters. Consequently, electron doses to the skin (tissue depth: 0.1 mm below 0.2 g/cm^2 of space suit shielding) were calculated from electron-proton spectrometer data.

Dose Versus Shield Depth

Doses to the blood forming organs (tissue depth: 5 cm) were found to average 0.66 of the doses observed to the skin. These dose averages were obtained by integration of outputs from the dual sensors of the Van Allen Belt Dosimeter. The value of 0.66 also is in good agreement with a value obtained by interpolation between crew-worn and film vault dosimeter results.

The sole difference between skin and eye doses (0.1 mm and 3.0 mm tissue depth, respectively) is the added dose to skin from electrons during extravehicular activities.

Quality Factor Versus Shield Depth

Film vault shielding was found to be relatvely ineffective from a simple dose reduction standpoint (table III). Despite the small dose reduction, however, quality factor could have decreased substantially if the dose reduction was solely due to filtering of lower energy particles. On the other hand, secondary buildup processes tend to increase quality factor as a function of shield depth. These competing effects could not be calculated accurately prior to the mission. Therefore, we have relied primarily on postmission nuclear emulsion analyses of the film vault dosimeters to determine space radiation quality as a function of shielding.

Comparison of emulsion data from the dosimeters worn by the crew and film vault dosimeters indicates that the filtering mechanism (reduced quality factor) is slightly dominant at shield depths up to 23.3 g/cm^2 aluminum. At blood forming organ depth, (5 cm tissue), quality factor is estimated equal to 1.5. In comparison, a quality factor of 1.6 is found for the crew-worn dosimeters beneath 0.3 g/cm^2 of tissue equivalent shielding.

Neutron Dosimetry

Details of the iridium/tantalum neutron dosimetry system have been published previously (2). Thermal (0.02 to 2.0 electronvolts) and intermediate (2.0 to 2×10^3 electronvolts) neutrons were found to contribute to crew dose equivalent at a combined rate of approximately 0.1 millirem/day.

Direct measurement of fast neutron fluence by suspended track analysis of crew worn nuclear emulsions was not possible due to the high track densities obtained on the Skylab missions. However, upper limit dose calculations have been made based on nuclear emulsion disintegration star analyses (to determine neutron production rates) and iridium/tantalum evaluation, assuming that all activation is due to tissue albedo. Both methods show excellent agreement with upper limit rates of approximately 12.5 millirem per day for fast neutrons with mean energy of approximately 1 megaelectronvolts.

CONCLUSION

Table IV summarizes the dosimetry results for each crewman of the Skylab missions. As indicated in this table, there were certain variations in passive dosimeter wearing habits which required adjustments for data comparison purposes.

Dose equivalents received by the Skylab 4 crewmen were the highest received in any NASA mission to date, but remained well within the limits established for the Skylab missions. Due to the low rates involved (for example, less than 100 millirem per day to blood forming organs), dose equivalents for each crewman remain well below the threshold of significant clinical effect. These dose equivalents apply specifically to long term effects such as generalized life shortening, increased neoplasm incidence, and cataract production. To place the mission values in perspective, the NASA career limits were 400 rem blood forming organs, 1200 rem skin, and 600 rem eye lens and were established from ancillary radiation exposure constraints recommended by the National Academy of Science and based upon a reference risk of doubling the incidence of lukemia and other neoplastic disease.

TABLE IV. SKYLAB MISSION DOSE COMPARISONS

CREWMAN AND PARAMETER	SKYLAB 2	SKYLAB 3	SKYLAB 4
Commander (rad, TLD)	1.62	3.67	8.02*
p+ EVA (rad, PRD)	0.13	0.01	0.25
e- EVA (rad, CALC)	1.07	1.50	1.34
Skin (rem)	3.66	7.37	14.17
Lens (rem)	2.59	5.87	12.83
BFO (rem)	1.60	3.63	7.94
Science Pilot (rad, TLD)	1.66	3.73†	7.36
p+ EVA (rad, PRD)	0.10	0.06	0.10
e- EVA (rad, CALC)	0.85	2.65	6.07
Skin (rem)	3.51	8.62	17.85
Lens (rem)	2.66	5.97	11.78
BFO (rem)	1.64	3.69	7.29
Pilot (rad, TLD)	1.81	4.21	6.80
p+ EVA (rad, PRD)	0.09	0.09	0.06
e- EVA (rad, CALC)	0.25	1.15	5.22
Skin (rem)	3.15	7.89	16.10
Lens (rem)	2.90	6.74	10.88
BFO (rem)	1.79	4.17	6.73
PRD Mean, 4 LOCS (rad)	1.98	4.71	7.81

Key:
*CALC wrist equivalent for 8.68 measured at ankle
†CALC wrist equivalent for 4.75 measured in sleep comp
Note: Quality factors used for proton doses to skin and eye = 1.6 quality factor for BFO = 1.5. Electron Dose applied to skin only: Quality factor = 1.0.
TLD = Thermoluminescent dosimeter
PRD = Personal Radiation dosimeter
BFO = Blood Forming Organs

This reference risk was taken to be a dose equivalent of 400 rem. These career limits also entail a statistical risk of nonspecific life shortening of from 0.5 to 3.0 years (3). The Skylab 4 crewman could fly a mission comparable to one 84-day Skylab 4 mission per year for 50 years before exceeding these career limits.

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TOXICOLOGICAL ASPECTS OF THE SKYLAB PROGRAM

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ABSTRACT

A toxicology support capability for the Skylab Program was used to ensure a safe, habitable spacecraft environment for the crewmen. From previous experience with closed-loop environmental operations (*e.g.*, submarines and manned chamber tests), it was known that trace-gas concentration buildup could cause mission-abort conditions. Therefore, the major toxicological consideration for the Skylab Program was to provide and maintain relatively low levels of contaminant gases in the spacecraft cabin atmosphere. To circumvent the possibility of the buildup of trace-gas levels, several preventive measures were taken. The most important measure was a screening test designed to eliminate materials that created serious outgassing problems. An atmospheric analysis of the completed Orbital Workshop was also made.

A significant toxicological problem developed before the Orbital Workshop was manned. The polyurethane skin insulation material was overheated. Laboratory tests indicated that the maximum allowable concentration value established for toluene diisocyanate probably had been exceeded and that excessive amounts of carbon monoxide probably were present in the Orbital Workshop. A successive series of atmospheric purges performed in the Orbital Workshop was followed by trace-gas analyses for toluene diisocyanate and carbon monoxide. When these analyses were completed, the crewmen safely entered the Orbital Workshop.

Trace-gas Orbital Workshop atmospheric samples were obtained during the Skylab 4 mission. Results of these analyses indicated the presence of approximately 300 compounds in the Orbital Workshop atmosphere; 107 of these compounds were identified. Because of the absorption characteristics of the sampling material, accurate quantitative data for all the identified compounds are unavailable. However, from these results, it is important to note that had an effective trace-gas removal capability not been contained within the environmental control system of the spacecraft, the atmospheric contamination buildup in the crew compartment could have been a serious problem.

INTRODUCTION

A toxicological support capability was established during the early developmental phases of the Skylab Program. From past experiences with closed-loop environmental operations, such as in submarines and manned chamber tests, it had been found that the buildup of trace contaminant gases could result in conditions which could cause mission termination. It was also recognized from the experience gained in the Apollo Program that the use of newly developed nonmetallic material, especially the fluoronated polymers, required toxicological considerations, and that special consideration be given to the testing for outgassing products.

It was known early in the program that the possibility of carbon monoxide buildup in the spacecraft cabin would also require special attention. None of the environmental control life support systems in previous spacecraft nor in Skylab were designed to provide carbon monoxide removal. It was therefore imperative that the selection of materials for use in the Skylab interior include consideration for the outgassing of carbon monoxide. It should be noted at this point that toxicological support provided for the Skylab Program included considerations not only for inhalation toxicity, but also ingestion, eye contact, and skin contact toxicity. Since the latter three areas of toxicology required attention so infrequently, they are not discussed in this paper.

PROCEDURES

To provide a safe, habitable, breathing environment for the Skylab crew, several measures were adopted early in the program. The most important of these was a nonmetallic materials screening program which was designed to eliminate those materials that would cause problems from their outgassed products. The screening program was based upon measuring the amounts of carbon monoxide and total organics outgassed per unit weight of each candidate material. Levels of acceptance were established for both carbon monoxide and total organics based upon the spacecraft habitable volume, the trace gas removal rate by the environmental control life support systems, and the cabin leak rate.

In the case where newly developed polymers were considered for use as electrical component potting compounds or electrical wire insulators, pyrolysis products of these materials were used to determine toxicological limits. The amount of material required to kill fifty percent of the exposed animals identified as lethal dose $_{50}$ (LD_{50}) was determined. In these cases, material selection included both outgassing data and LD_{50} information.

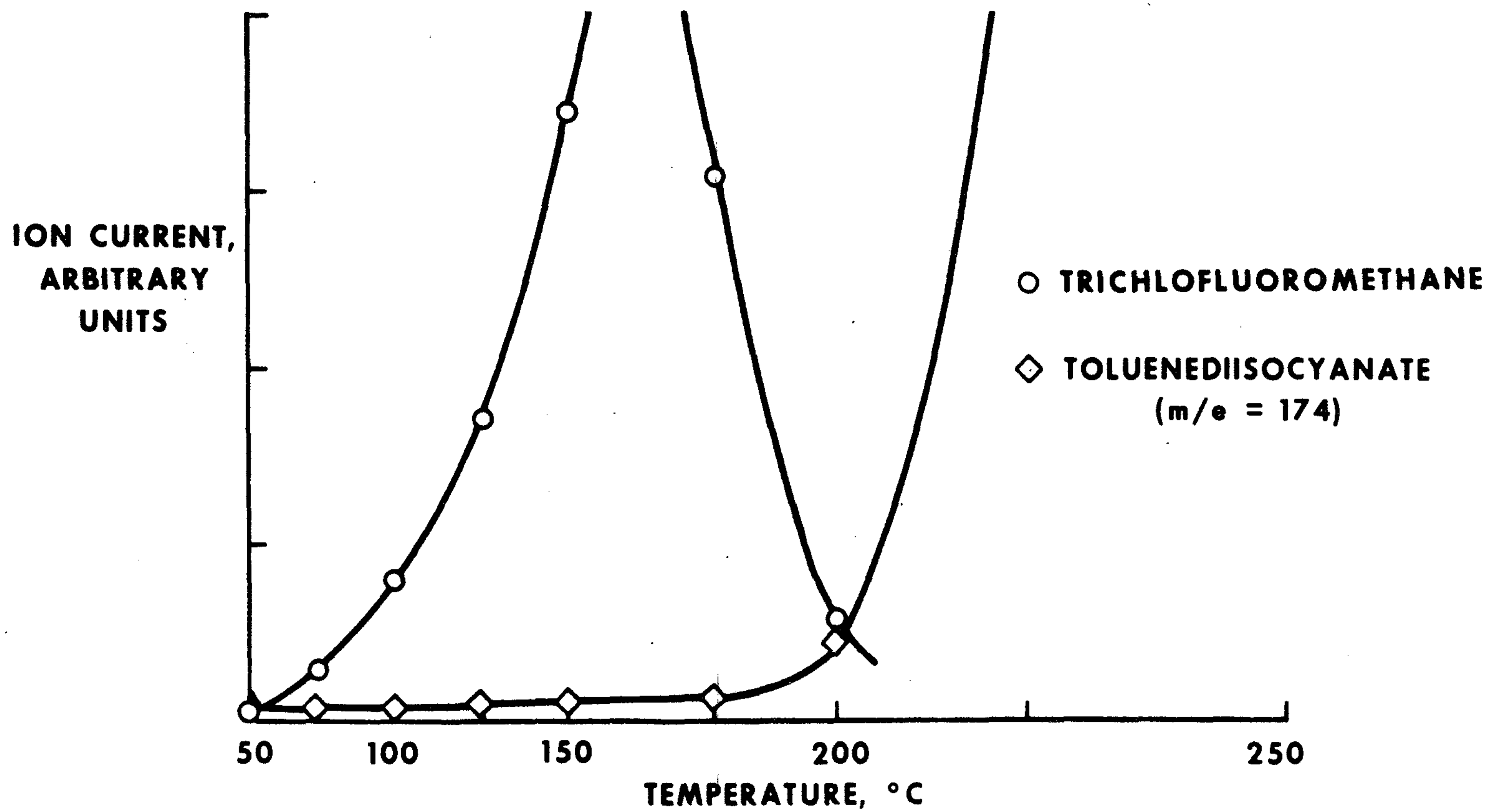
In support of these inhalation exposures, chemical analyses, using mass spectral-gas chromatographic procedures, were performed to determine the chemical compound(s) contained in the pyrolysis products that could cause the toxic effect. These analytical procedures were also performed when a waiver was requested on any candidate spacecraft material that failed the carbon monoxide and total organics screening tests.

PROBLEMS

Following the loss of the Skylab 1 micrometeoroid shield, a significant toxicity problem developed as a direct result of the over heating of the Orbital Workshop interior wall insulation material. The wall temperature sensors indicated that the interior insulation of the Orbital Workshop had attained a projected temperature of 177° C (350° F) on the skin-side of the insulation and 71° C (160° F) on the interior volume-side of the spacecraft insulation. Since the insulation was known to be a rigid polyurethane foam, it was realized that a potential hazard could develop as a result of the decomposition of the polymer to produce an isocyanate derivative. Of secondary concern was the accelerated offgassing rate of the entire nonmetallic materials contained in the Skylab habitable volume. Enough time was fortunately available for the Life Sciences Toxicology Laboratory to exercise a rapid literature search for information concerning polyurethane foam decomposition and the related toxicity problems. An investigation was also initiated to determine the outgassing characteristics of the foam under the existent abnormal Skylab 1 environmental conditions.

SOLUTIONS

Using a piece of foam identical with that in Skylab 1 (same chemical lot and age), a solids probe mass spectral analysis was conducted. In figure 1 (1) the graphic results show that polymer decomposition begins at about 200° C (392° F). It should be noted that toluene diisocyanate was detected in trace quantities from 50° C (122° F) to about 200° C (392° F). It was learned from communication with the manufacturer of the foam that an excess of toluene diisocyanate is used in the processing of a rigid foam. The excess toluene diisocyanate was apparently diffusing from the foam during the lower temperatures prior to thermal decomposition. It is also noted in figure 1 that the blowing agent, trichlorofluoromethane, contained in the foam, reached a maximum



Key: m/e = mass/electron charge

Figure 1. Polymer decomposition on heating.

release rate at about 150° C (302° F). No accurate quantitative results were available from these analyses due to the unavailability of toluene diisocyanate standards.

Information was obtained from the manufacturer of the Orbital Workshop for approximated increases in concentration values in the spacecraft for both toluene diisocyanate and carbon monoxide; these were 0.2 ppm toluene diisocyanate/day at 79° C (175° F) and 2 ppm carbon monoxide/day at 143° C (290° F). The D. A. Reilly analytical procedure (2) was used by this manufacturer's reporting group but, at the time of the over heating of the polyurethane foam, there existed no spacecraft requirements for acceptable atmospheric concentrations of toluene diisocyanate. The maximum allowable exposure (8-hour weighted average) limits established by the Occupational Safety and Health Administration (3) for toluene diisocyanate is 0.14 mg/m^3 [0.02 ppm standard temperature and pressure (STP)]. Reports in the literature (4,5,6,7,8,9,10) all substantially support this exposure limit.

Prior to the launch of the Skylab 2 crew, gas analysis tubes were prepared for space flight use. Two types of detector tubes were furnished the crew for the atmospheric analysis. These were of the colorimetric design and included one type of tube for carbon monoxide and another for toluene diisocyanate. The lower sensitivity of the carbon monoxide tubes was 11 mg/m^3, and for the toluene diisocyanate tubes, 0.14 mg/m^3. Atmospheric samples were taken by using a syringe-type pump to flow air through the analyzer tubes.

Prior to the entry of the crew into Skylab 1, two precautionary measures were undertaken to ensure that the habitable areas were safe for manned operations. The first was a series of pressurization-depressurization cycles of the Skylab 1 atmosphere designed to discharge and dilute any contaminating gases of potentially toxic levels. The second measure consisted of the crew's assessment of the carbon monoxide and toluene diisocyanate contents by use of the supplied analyzer tubes. The results of their analyses indicated no detectable toluene diisocyanate and an extrapolated 5 mg/m^3 level of carbon monoxide.

The crew energized the Skylab 1 Environmental Control Life Support System which contained 9.02 kg (20 lb) of activated carbon, specifically designed to remove trace levels of contaminating compounds. From prior tests it was known that the spacecraft-type activated carbon would very efficiently remove toluene diisocynate. After a thirty-minute atmospheric circulation period, the crew was given instructions

to make entry into the Skylab 1 for manned operations. This mission and Skylab missions 3 and 4 were accomplished without any other atmospheric trace gas problems.

In addition to potential offgassing problems from excessive internal temperatures in the Orbital Workshop, a leak was suspected in the coolant system of the spacecraft. Therefore, it was of significant interest to toxicology, materials, and safety personnel to determine the compositions and concentrations of any atmospheric trace contaminants. The coauthor of this paper conceived and directed the development of a device that was used during the final mission for gathering this needed information.

The device consisted of two small glass tubes, mounted in parallel in an aluminum cartridge, such that an atmospheric gas flow could pass equally through both tubes at the same time. Each of these tubes was partially filled (4.5 ml/tube) with a gas chromatographic absorbent material. Approximately 60 liters (STP) of cabin atmosphere were passed through the device during a time span of 15 hours. Three such samples were taken by the Skylab 3 crew on mission days 11, 46, and 77.

The analyses of the absorbed contents of the three samples (three pairs of tubes) were accomplished under NASA contract[1] and the coauthor's supervision. The results of these analyses indicated the presence of more than 300 compounds in the Skylab atmosphere during the occupancy of the Skylab 3 crew. Of this number, 107 were identified by mass spectral methods. The molecular weights for the identified compounds ranged from 60 to 584. A list of these compunds including the atmospheric concentration values are delineated in table I. Data from the compounds detected and identified revealed that there was no coolant fluid leaking into the interior of the Orbital Workshop.

When the three atmospheric samples taken on mission days 11, 46, and 77 were compared, the results (fig. 2) indicated only minor differences in the levels of contamination. This would indicate that a state of equilibrium had been attained earlier between the gas generation rates of the contaminant sources and the environment control life support systems removal rate.

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[1]NASA Contract, NAS9-13457, Mod. 2S. (Principal Investigator: Albert Zlatkis, Ph.D., University of Houston, Houston, Texas.)

TABLE I. VOLATILES IN THE ATMOSPHERE OF SKYLAB 3

Identified Chemical Cmpd	MD11 conc (ppb)	MD46 conc (ppb)	MD77 conc (ppb)	Remarks
difluorodichloro-methane	36.9	59.8	193.0	not quantitative
Freon-112® Freon-113®	5907.0	8653.0	8446.0	not quantitative
siloxane, normal, n=2	79.5	7.0	96.6	not quantitative
cyclohexane	28.4	13.0	41.4	not quantitative
n heptane + monofluoro-dichloromethane	96.5	33.8	77.3	not quantitative
acetone	7895.0	7098.0	2760.0	not quantitative
C_8 alkane	11.4	7.8	22.1	not quantitative
C_8 alkane	17.0	13.0	27.6	not quantitative
heptene	5.7	2.6	82.8	not quantitative
heptene	88.0	52.0	116.0	not quantitative
n octane + heptene	28.4	39.0	27.6	not quantitative
ethylacetate	454.0	390.0	221.0	not quantitative
2-butanone	1505.0	1222.0	665.0	not quantitative
siloxane, normal, n=3	105.0	117.0	138.0	not quantitative
propanol + Freon ($C_2Cl_4F_2$ tent.)	713.0	1144.0	856.0	propanol in low concentration
siloxane, cyclic, n=3	62.5	26.0	-	following sub-stance quantitative
benzene + diacetyl	116.0	70.1	38.6	diacetyl minor
C_9 alkane	22.7	13.0	19.3	
4-methyl pentanone-2 + siloxane, cyclic, n=4	1990.0	1625.0	996.0	siloxane minor
trimethylsilanol (tent.)	-	93.6	152	
dichloroethane	454.0	224.0	213.0	
toluene + tetrachloro-ethylene	1678.0	1040.0	1717.0	tetrachloroethylene minor
C_{10} alkane + siloxane, normal, n=4	42.6	50.2	152	
C_{10} alkane	19.9	46.8	41.4	
C_{10} alkane	5.7	7.8	8.3	

TABLE I. continued

Identified Chemical Cmpd	MD11 conc (ppb)	MD46 conc (ppb)	MD77 conc (ppb)	Remarks
C_4 benzene	33.7	13.0	49.7	
C_4 benzene	19.9	10.4	16.6	
butoxyethanol	-	-	4305.0	
silicon comp., MW 504	11.4	15.6	22.1	
C_4 benzene	11.4	13.0	13.8	
C_4 benzene	2.8	5.2	11.0	
dichlorobenzene	25.6	13.0	24.8	
C_5 benzene	25.6	13.0	24.8	
siloxane, cyclic, n=7	179.0	98.8	74.5	
C_5 benzene + C_{13} alkane	19.9	10.4	19.3	
C_4 benzene + C_5 benzene + siloxane, MW 518	65.3	88.4	82.8	
silicon, comp., MW 541	62.4	31.2	74.5	
benzaldehyde	114.0	62.4	102.0	not quantitative
C_4 benzene + C_5 benzene + silicon comp., MW 320	17.0	3.0	5.4	
C_5 benzene + C_{12} alkene + silicon comp., MW 584	42.6	31.2	46.9	silicon minor
C_4 benzene + C_{12} alkene	25.6	39.0	11.0	
C_2 styrene + C_4 benzene	45.4	33.8	74.5	
benzonitrile	45.4	39.0	41.4	
C_5 benzene	45.4	23.4	46.9	
C_5 benzene + C_{14} alkane	25.6 31.2	10.4 20.8	24.8 2.7	
C_5 benzene	170.0	13.0	2.7	
acetophenone	59.6	20.8	77.3	not quantitative
silicon comp., MW 358	56.8	39.0	44.2	
dimethyldihydroindane (tent.)	11.4	7.8	13.8	
C_{15} alkane	22.8	23.4	35.1	
C_5 benzene	11.4	7.8	19.3	
naphthalene	90.9	59.8	113.0	

TABLE I. continued

Identified Chemical Cmpd	MD11 conc (ppb)	MD46 conc (ppb)	MD77 conc (ppb)	Remarks
n-decane	190.0	93.6	127.0	
4-methyl-4-pehtene-2-one	176.0	93.6	124.0	
C_{11} alkane	19.9	23.4	27.6	
ethylbenzene + siloxane normal, MW 384 + siloxane, MW 370	116.0	52.0	77.3	
p-xylene	131.0	153.0	177.0	
m-xylene	272.0	164.0	166.0	
siloxane, normal, n=5 + C_{12} alkane	68.2	31.2	44.2	alkane minor
C_{12} alkane	19.9	52.0	11.0	
silicone comp., MW 341	42.6	26.0	2.7	
aliphatic alcohol + C_{12} alkane	148.0	67.6	63.5	
o-xylene	148.0	67.6	63.5	
C_3 benzene	1.9	4.7	5.4	
siloxane, normal, n=5	17.0	13.0	16.6	
C_{12} alkane + silicon comp., MW 278	54.0	31.2	60.7	
siloxane, MW 415 + styrene	31.2	15.6	19.3	
C_3 benzene	42.6	28.6	35.9	
C_{12} alkane	22.7	10.4	30.4	
A hydroxyketone (tent.)	582.0	348.0	331.0	
limonene	273.0	159.0	138.0	
nonene	102.0	291.0	35.9	
siloxane, cyclic, n=6	79.5	122.0	157.0	
2-octanone	25.6	41.6	80.0	
C_3 benzene silicon comp., MW 285	11.4	13.0	13.8	
methylstyrene + n-dodecane	25.6	10.4	5.4	
siloxane, normal, n=6	33.7	20.8	33.1	
C_3 benzene	19.9	13.0	22.1	

TABLE I. concluded

Identified Chemical Cmpd	MD11 conc (ppb)	MD46 conc (ppb)	MD77 conc (ppb)	Remarks
methylnaphthalene	48.3	28.6	33.1	
methylnaphthalene	2.8	2.6	2.7	
C_{17} alkane	45.4	33.8	46.9	

CHROMATOGRAMS

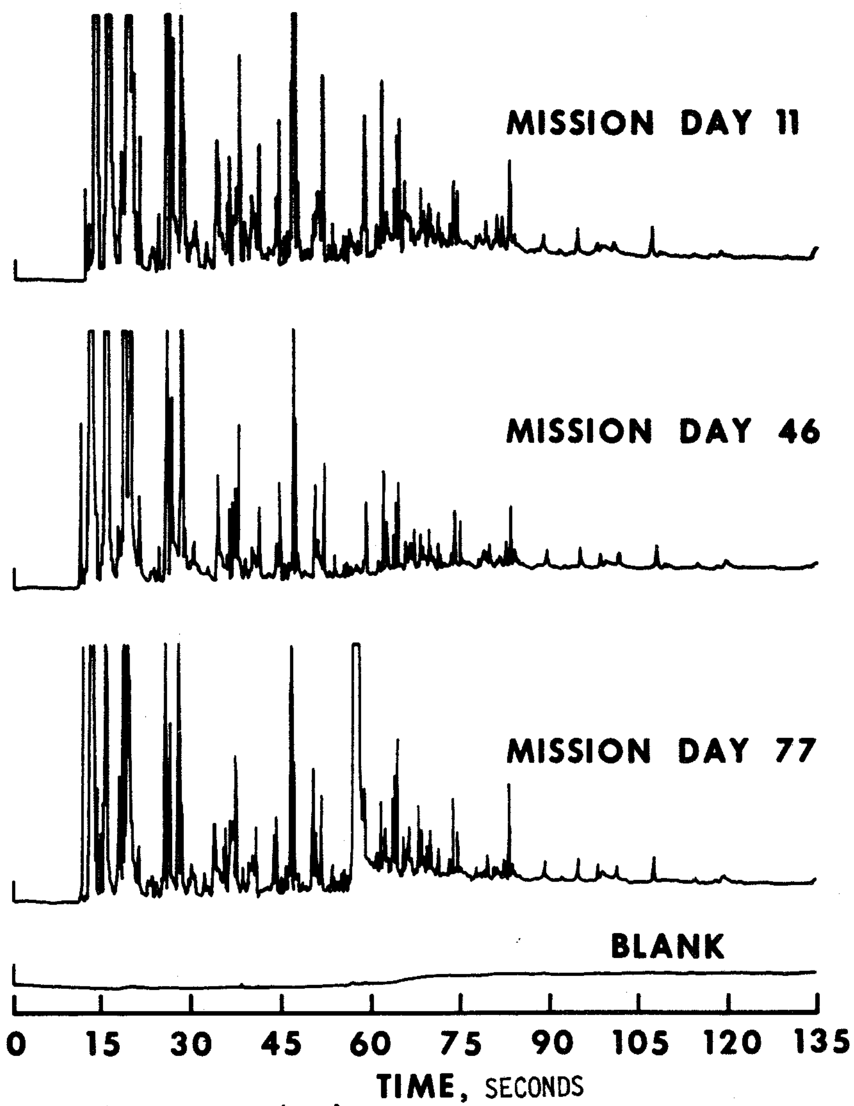

Figure 2. Comparison of the tracings of the three atmospheric samples taken during the Skylab 3 mission.

CONCLUSION

The experiences and data gained in the Skylab Program have demonstrated that the crew was provided with as safe an environment as could be attained using the current state-of-the-art trace gas removal technology. The knowledge gained in solving the trace contaminant problems encountered in the Skylab program will greatly aid in providing new and safe, habitable spacecraft environments for the future missions of man in space.

ACKNOWLEDGEMENT

The authors of this paper wish to acknowledge the important contribution of Dr. E. S. Harris of the National Institute for Occupational Safety and Health (formerly Head of the NASA-JSC Toxicology Laboratory) in directing the toxicology program in support of Skylab.

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NEUROPHYSIOLOGY

EXPERIMENT M-131. HUMAN VESTIBULAR FUNCTION

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Experiment M-131 comprises three subtasks which will be reported separately, namely, 1) susceptibility to motion sickness, 2) thresholds for perception of angular acceleration as indicated by the oculogyral illusion, and 3) the perceived direction of internal and external space.

I. SUSCEPTIBILITY TO MOTION SICKNESS

Abstract

Under experimental conditions tests were conducted on and after mission day eight by which time the astronauts were adapted to working conditions in the workshop. Stressful accelerations were generated by requiring the astronauts, with eyes covered, to execute standardized head movements (front, back, left, and right) while in a chair that could be rotated at angular velocities up to 30 revolutions/minute. The selected endpoint was either 150 discrete head movements or a very mild level of motion sickness. In all rotation experiments aloft, the eight astronauts tested (the Commander of Skylab 2 did not participate) were virtually symptom free, thus demonstrating lower susceptibility to motion sickness aloft than in preflight and postflight tests. The absence of an endpoint aloft, however, limited quantitation. Inasmuch as the eyes were covered and the canalicular stimuli were the same aloft as on the ground, it would appear that lifting the stimulus to the otolith organs due to gravity was an important factor in reducing susceptibility to motion sickness even though the transient linear and coriolis acceleration generated under the test conditions were substantial and abnormal in pattern.

Under operational conditions seven of the nine crewmen experienced motion sickness, five of the seven while in orbit. The administration of antimotion sickness drugs made it difficult or impossible accurately to determine the level of susceptibility at all times. The Skylab 2 crewmen did not experience clear-cut symptoms aloft and only the Scientist Pilot experienced seasickness; indeed, the Commander and Pilot did not take drugs yet remained symptom free throughout the mission. Among the Skylab 3 crew the Pilot experienced motion sickness shortly

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after transition into orbit, the earliest diagnosis on record. The two remaining crewmen first experienced motion sickness shortly after entering the workshop. For a period of three days symptoms were controlled by drugs and by restricting activity. Recovery was complete by mission day seven. The Skylab 4 crewmen were scheduled to take antimotion sickness medication but only the Scientist Pilot avoided symptoms.

Only self-evident findings are used as points of departure in discussing motion sickness. These findings contribute to our knowledge of the ways and means by which weightlessness qualifies as a unique motion environment. Some attempt is made to explain the findings and to indicate their main implications of a practical and theoretical nature.

Introduction

Prior to Skylab missions, nine U.S. and four U.S.S.R. crewmen reported motion sickness in orbital flight (table I-I). Soviet investigators have described in detail vestibular side effects experienced by cosmonauts on transition into weightlessness (1 through 8), and it is noteworthy that reflex motor phenomena were reported far more frequently than was motion sickness. Postural illusions were experienced immediately after transition into orbit, and, while usually short-lived, some cosmonauts continued to experience the illusion until the g-load reappeared that was associated with reentry. Illusions evoked by rotary motions of the head or head and body (sensations of turning and dizziness) were experienced not only early in flight but also over prolonged periods. Among the 24 cosmonauts 4 experienced motion sickness, an incidence of about 17 percent. It is interesting that all incidents occurred in early missions, an incidence of about 36 percent.

The classical example of motion sickness experience in space flight was provided by Titov. For a very brief period immediately after transition into orbit Titov felt that he was flying upside down. Soon thereafter he described dizziness associated with head movements and sometime between the fourth and seventh orbit (six or more hours) he became motion sick, the first recorded instance in space flight.

In the U.S. space program motion sickness aloft was not reported until the Apollo missions (9), although seasickness after splashdown was not an infrequent occurrence. In the Apollo command module where stimulus conditions were far more favorable for eliciting motion sickness than in the Mercury program, on the moon, or in the Gemini command module, 9 among 25 Apollo astronauts were motion sick. In the Mercury spacecraft the astronauts were restrained in their couches, helmets (which were removed only occasionally) prevented quick head movements and the visual cues were adequate and plentiful. In the Gemini spacecraft helmets were not worn but there was limited opportunity for free-floating activities. The 12 astronauts exposed to Lunar conditions

did not experience motion sickness, but inasmuch as all were insusceptible in orbital flight, the benefit of a franctional g-loading was not tested. Moreover, their helmets prevented quick head movements except about the vertical axis and visual cues were excellent.

TABLE I-I. MANNED SPACE FLIGHT PROGRAMS

United States			Russia		
Program	Number of Space Pilots	Incidence of Motion Sickness	Program	Number of Space Pilots	Incidence of Motion Sickness
Mercury	6	0	Vostok	6	1
Gemini	16	0	Voskhod	5	3
Apollo Command Module	25	9	Soyuz	13	0
Apollo Lunar Landing	12	0			

In this report a distinction is made between two categories of vestibular side effects (10). One category comprises a great variety of "immediate reflex motor responses", such as postural illusions, sensations of rotation, nystagmus, and what often is termed dizziness or vertigo. The other category, motion sickness, is a delayed epiphenomenon (superimposed on any responses in the reflex category), involving vestibular influences that cross a temporary or "facultative linkage", to reach nonvestibular sites where first-order responses that lead to motion sickness symptoms have their immediate origin. First-order responses may, in turn, elicit second and higher order responses or complications until the organism is generally involved. Symptoms of motion sickness are usually elicited when too rapid a transition is made from one motion environment to another (11). The primary or essential etiological factor is of vestibular origin, inasmuch as under such a transition persons with loss of vestibular function do not become motion sick (12, 13). Secondary etiological factors are always operative, however. In healthy, normal persons visual inputs and psychological factors are usually the most important ones; in some motion environments just opening the eyes may precipitate motion sickness. In most motion environments visual inputs are not essential for the elicitation of motion sickness; blind persons who have never perceived light may readily become sick (14).

Procedure

Astronauts

Table I-II summarizes findings in the nine Skylab astronauts dealing with their susceptibility to motion sickness in different motion environments and their responses during tests of vestibular function.

The Skylab 2 Commander had participated in the Gemini V mission and, along with the Skylab 3 Commander, took part in the Apollo 12 mission which included landing on the Moon; neither had reported any symptoms of motion sickness during those missions. In other motion environments individual differences in susceptibility were demonstrated in a range below average susceptibility.

Functional tests of the astronauts' vestibular organs revealed no definite abnormalities. These tests included a postural equilibrium test battery for which the scores, although not shown in table I-II were within the normal range. Of particular interest in view of the physiological deafferentation of the otoliths in weightlessness, however, are the low values for ocular counterrolling, which is a test of otolithic function. The counterrolling index (one-half the maximum roll when tilted right and left) was only 158 minutes of arc in the Skylab 2 Commander and Skylab 3 Scientist Pilot; whereas, among 550 normal subjects the average was 344 minutes of arc (15).

TABLE I-II

HISTORY OF MOTION SICKNESS AND VESTIBULOMETRIC FINDINGS IN THE NINE ASTRONAUTS

SKYLAB	ASTRONAUT	AGE	HISTORY OF MOTION SICKNESS								CANAL FUNCTION		OTOLITH FUNCTION	CORIOLIS SICKNESS SUSCEPTIBILITY INDEX
			AIRCRAFT		0G MANEUVERS (NOT KC135)		SPACE FLIGHT		SEA MOD. TO HEAVY		CANAL THRESHOLDS OF RESPONSE	MODIFIED FITZGERALD-HALLPIKE	OCULAR COUNTER-ROLLING	
			EXPERIENCE	SYMPTOMS	EXPERIENCE	SYMPTOMS*	EXPERIENCE	SYMPTOMS	EXPERIENCE	SYMPTOMS		PREPONDERANCE		
2	CDR	42	>2000 h	-	>100 TIMES	4	GEMINI V APOLLO XII	-	1-5 TIMES	SLIGHT	WITHIN NORMAL LIMITS	INSIGNIFICANT	158 LOW NORMAL	10.2
	SPT	40	>1000 h	-**	25-50 TIMES	4	NONE	NA†	1-5 TIMES	SLIGHT	WITHIN NORMAL LIMITS	INSIGNIFICANT	300 NORMAL	8.2
	PLT	40	>2000 h	-	>100 TIMES	2	NONE	NA	>100 TIMES	-	WITHIN NORMAL LIMITS	SIGNIFICANT (RETEST INDICATED)	374 NORMAL	19.8
3	CDR	40	>1000 h	-**	>100 TIMES	16‡	APOLLO XII	-	10-50 TIMES	SLIGHT	WITHIN NORMAL LIMITS	SIGNIFICANT (RETEST INDICATED)	365 NORMAL	23.1
	SPT	41	>1000 h	-	>100 TIMES	4	NONE	NA	>100 TIMES	MOD.	WITHIN NORMAL LIMITS	INSIGNIFICANT	158 LOW NORMAL	26.4
	PLT	36	>2000 h	-	>100 TIMES	4	NONE	NA	5-10 TIMES	SLIGHT	WITHIN NORMAL LIMITS	INSIGNIFICANT	332 NORMAL	19.2
4	CDR	40	>1000 h	-**	10-25 TIMES	16	NONE	NA	10-50 TIMES	SLIGHT	WITHIN NORMAL LIMITS	INSIGNIFICANT	494 NORMAL	7.5
	SPT	36	>1000 h	-**	>100 TIMES	8	NONE	NA	1-5 TIMES	SLIGHT	WITHIN NORMAL LIMITS	INSIGNIFICANT	261 NORMAL	8.9
	PLT	43	>1000 h	-**	>100 TIMES	8	NONE	NA	0	NA	WITHIN NORMAL LIMITS	INSIGNIFICANT	254 NORMAL	52.8

*MAXIMUM MALAISE LEVEL
**MILD SYMPTOMS ON RARE OCCASIONS
† NOT APPLICABLE
‡ EMESIS

A test (16) for grading susceptibility to motion sickness and yielding a single numerical score (Coriolis Sickness Susceptibility Index) was carried out. The scores on the astronauts are compared with susceptibility in 624 normal subjects in figure I-1. It should be pointed out, however, that it was demonstrated prior to Skylab missions that the scores obtained in this test do not predict susceptibility to motion sickness in the weightless phase of parabolic flight (17). The results of such a comparison are shown in table I-III. It is seen that susceptibility on the ground predicted susceptibility aloft in about 22 percent of the subjects.

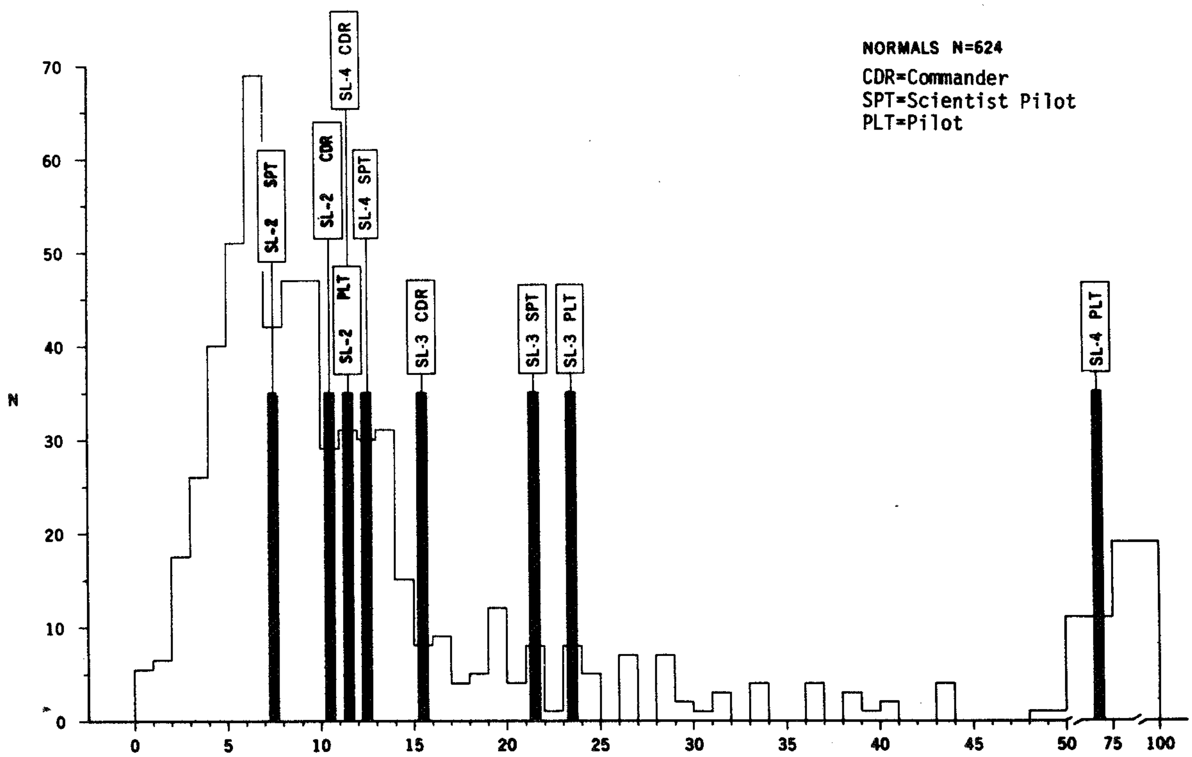

Figure I-1. Frequency distribution of motion sickness susceptibility scores of 624 normal subjects with scores of the nine Skylab astronauts indicated. The method used was similar to that used in Skylab missions.

TABLE I-III. CHANGES IN SUSCEPTIBILITY TO MOTION SICKNESS AMONG 74 SUBJECTS AS DETERMINED BY COMPARING SYSTEMATIC QUANTITATIVE MEASUREMENTS MADE DURING WEIGHTLESS PHASES OF PARABOLIC FLIGHT AND ON THE GROUND.

	Decreased			
Subjects	Endpoint Reached	Endpoint Not Reached	About Same	Increased
74	20	15	16	23

Stimulus Conditions

Under *operational conditions* the astronauts made major transitions from land to orbital flight, to sea, and back to land. While aloft, transitions were made between the command module and the workshop and, during extravehicular activity, between the spacecraft and the outer environment. During entry there were variations in g-loading that terminated at splashdown, followed by transitions from the command module to the recovery aircraft carrier, and finally from the carrier to land.

In considering the transition from one motion environment to another it is necessary to take into account not only the "new" environment, but also the current status of adaptation effects acquired in antecedent environments. Skylab conditions in the workshop were far more stressful than those in the command module, and highly complicated vestibular and visual inputs were encountered in the workshop. Accelerative stimuli there were associated with passive as well as active movements and visual stimuli were, potentially at least, disorienting. Thus, the opportunity was present to reveal individual differences in susceptibility to motion sickness, based on vestibular inputs as well as on complexly interacting vestibular and visual stimuli.

At sea the astronauts were passively exposed to motion environments that stimulated the vestibular organs. The active execution of head (and body) movements contriubted angular and linear accelerations that, combined with the passive exposure to sea motions, generated cross-coupled angular accelerations (stimulating the semicircular canals at suprathreshold levels) and Coriolis accelerations stimulating the otolithic receptors (18 through 20).

Under *experimental conditions* (on and after mission day 8 aloft and on the ground) a stressful motion environment was generated by requiring the astronauts, with eyes covered, to execute head movements while in a rotating litter chair (figs. I-2 and I-3). The rotating litter chair could be revolved at constant velocities up to 30 revolutions per minute (rpm)(21). The experimental procedures involved alternate clockwise and counterclockwise rotations, but rotation was more often clockwise than counterclockwise. Each discrete head and body movement ("over" and "back") through an arc of 90 degrees in each of the four cardinal directions (front, back, left, right) required one second, and was followed by a "hold" for one second in the upright position. Movements were made in sets of five (the forward movement was executed twice), and after each set the astronaut kept his head in the upright position for 20 seconds. The maximum number of head movements required in a test was 150 (one endpoint) unless mild motion sickness (the other endpoint) was reached earlier.

The rotating litter chair was used in the stationary as well as the rotating mode. In the stationary mode when head movements were executed aloft, the canals were stimulated in the same way as on the ground, but the otolith organs were stimulated in an abnormal manner because the impulse linear accelerations generated were not combined with a gravity vector as they would have been on the ground. These impulse linear accelerations were transient but well above threshold for stimulation of the otolith receptors. When the rotating litter chair was rotating, the intensity of the stimuli generated by head movement was a function of the rotational velocity, and although the angular and cross-coupled angular accelerations stimulating the semicircular canals aloft were the same as on the ground, the impulse and Coriolis accelerative forces generated aloft were not combined with a gravitational vector. These forces, nevertheless, were substantial at all levels of angular velocity used, and at 30 rpm the centripetal force was, respectively, 0.3 g and 0.6 g at radii of 1 and 2 feet.

The Diagnosis of Motion Sickness

The diagnostic criteria for motion sickness used in the Skylab experiments are summarized in table I-IV and are described in detail elsewhere (22). In brief, the severity of motion sickness symptoms was given a numerical score; sixteen points and above comprised the range of "frank motion sickness", and less than sixteen points, the range of "mild motion sickness".

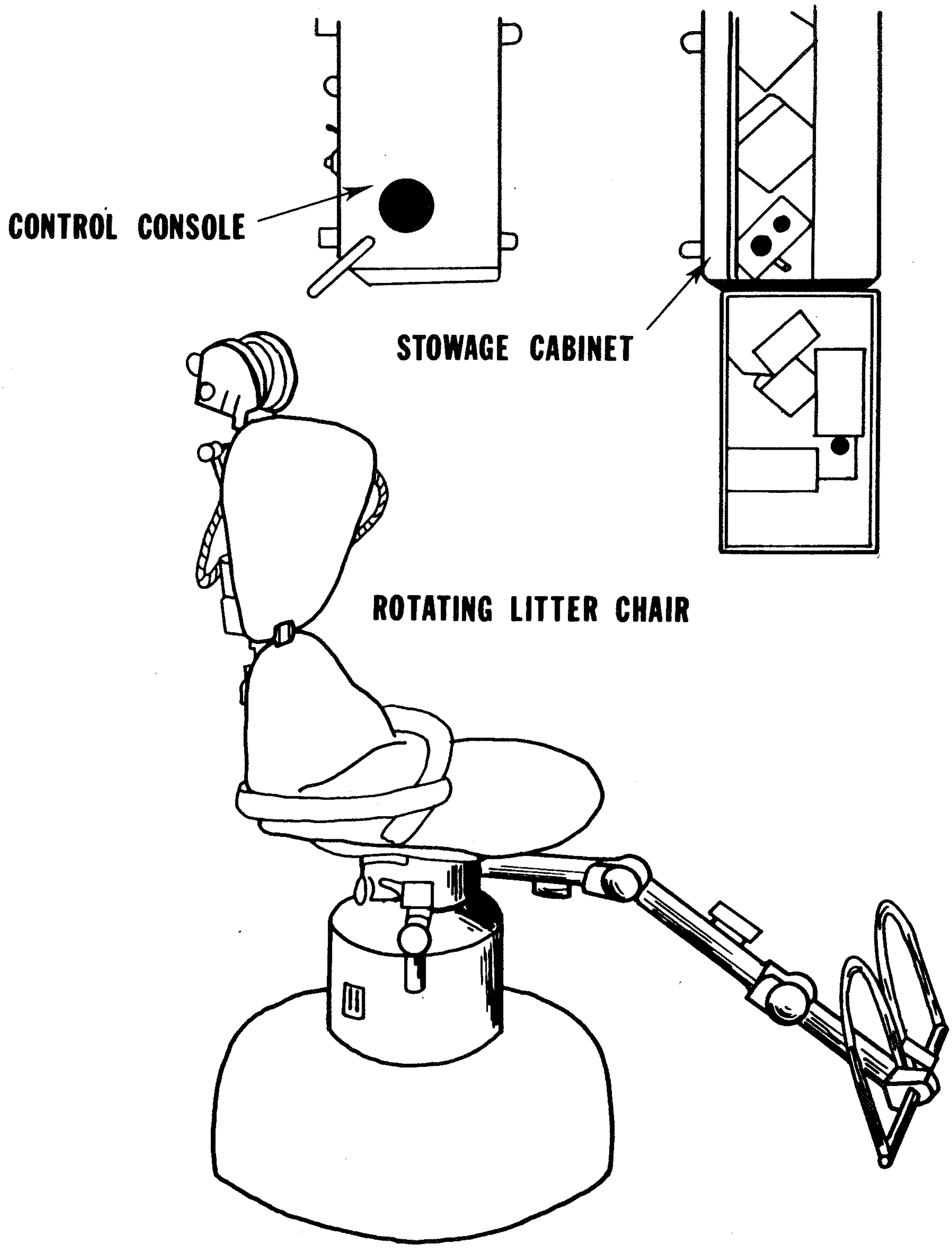

Figure I-2. The rotating litter chair motion sickness test mode.

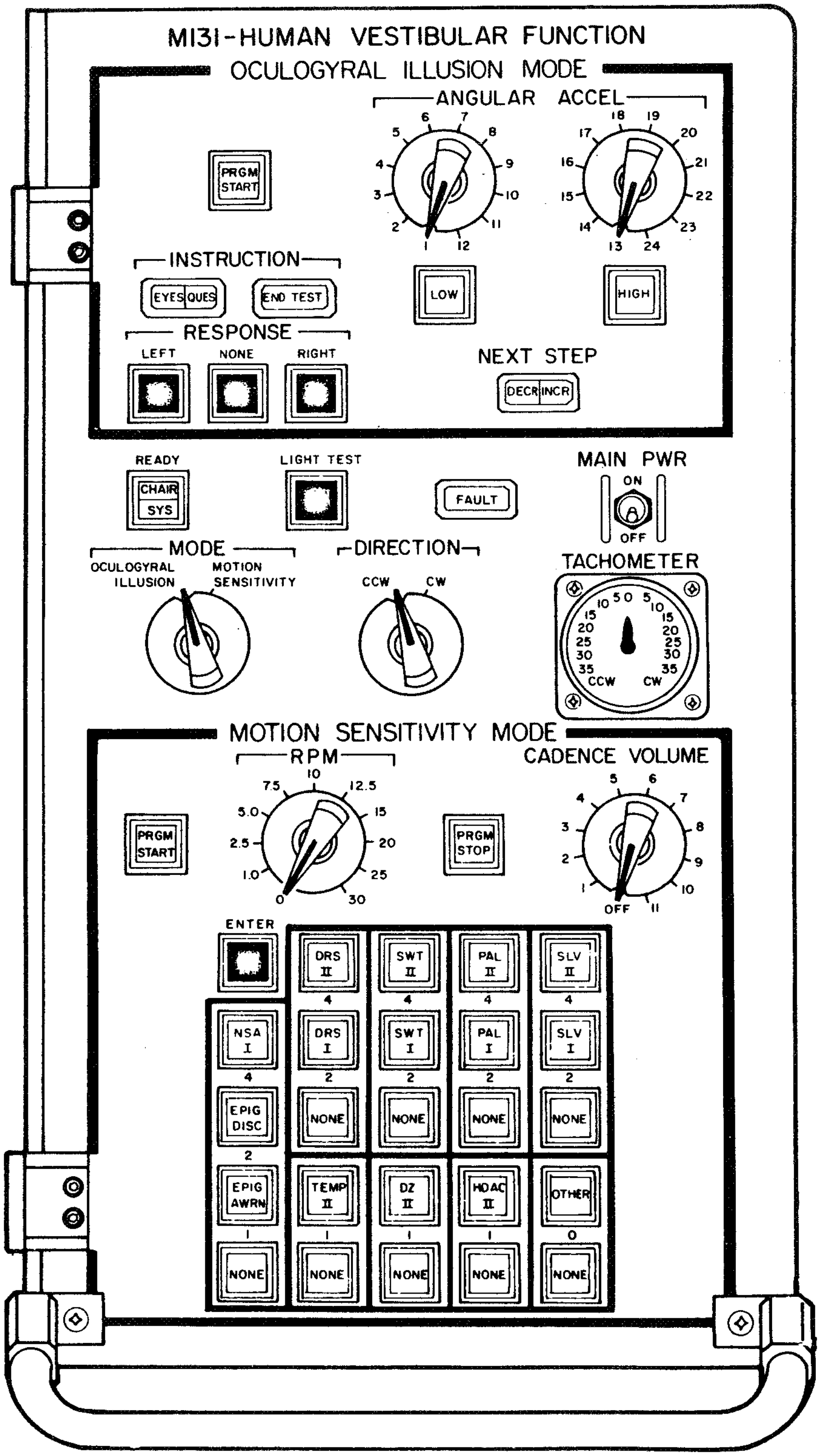

Figure I-3. Console used in connection with the rotating litter chair.

TABLE I-IV

Diagnostic Categorization Of Different Levels Of Severity Of Acute Motion Sickness

Category	Pathognomonic 16 points	Major 8 points	Minor 4 points	Minimal 2 points	AQS* 1 point
Nausea syndrome	Nausea III,† retching or vomiting	Nausea II	Nausea I	Epigastric discomfort	Epigastric awareness
Skin		Pallor III	Pallor II	Pallor I	Flushing/Subjective warmth ≥II
Cold sweating		III	II	I	
Increased salivation		III	II	I	
Drowsiness		III	II	I	
Pain					Headache (persistent) ≥II
Central nervous system					Dizziness (persistent) Eyes closed ≥II Eyes open III

Levels of Severity Identified by Total Points Scored

Frank Sickness (FS)	Severe Malaise (M III)	Moderate Malaise A (M IIA)	Moderate Malaise B (M IIB)	Slight Malaise (M I)
≥16 points	8 – 15 points	5 – 7 points	3 – 4 points	1 – 2 points

*AQS – Additional qualifying symptoms
†III – severe or marked, II – moderate, I – slight

Under *experimental conditions* the diagnosis of acute motion sickness was aided by the close temporal relation between exposure to stressful stimuli and elicitation of responses. In all Skylab experiments the motion sickness endpoint, moderate malaise (M II A) (a point score of 5 to 7), was of very mild intensity; the avoidance of more severe symptoms was an operational requirement.

An observer in collaboration with the subject estimated the severity of each predesignated symptom and recorded any "other symptom" not mentioned in table I-IV. There was always adequate time after execution of each set of head movements to make the estimates and record them by depressing the appropriate push-buttons in the response matrix of the rotating litter chair Control Console. One-hundred and fifty head movements or a score $\geq$ 5 points automatically triggered a signal that the test had been completed.

Under *operational conditions* the astronauts' ability to diagnose different levels of severity of motion sickness was enhanced by their training in connection with the preflight experimental evaluation of motion sickness susceptibility. Nonetheless, under operational conditions diagnosis was more difficult than under experimental conditions

because the identification of the stressful stimuli was not always easy, and the symptomatology of "chronic" or prolonged motion sickness (experienced aloft) differed in some respects from that of acute motion sickness.

Medication

The astronauts in Skylab 2 and Skylab 3 carried with them antimotion sickness capsules containing l-scopolamine 0.35 milligrams + d-amphetamine 5.0 milligrams; in addition to this drug the Skylab 4 crew took along the drug combination promethazine hydrochloride 25 milligrams + ephedrine sulfate 50 milligrams, drugs which had proven to be effective under experimental (23) and operational conditions (24). This drug combination acts by raising the stimulus thresholds for eliciting motion sickness responses and is effective in any motion environment. Indeed, preflight drug evaluation tests were carried out on all nine astronauts; endpoints were not reached even at angular velocities of 20 rpm for the Skylab 2 crewmen and 30 rpm for the Skylab 3 and Skylab 4 crewmen.

Results

It is convenient to present the findings dealing with motion sickness first under "operational conditions" then under "experimental conditions".

Operational Conditions

Attention will be mainly centered on motion sickness during the orbital phase of the mission and will be discussed with the aid of Figure I-4. The horizontal lines reflect two things. First, the periods during which the astronauts were based in the command module and in the workshop during the first week in orbit. Second, the thickness and continuity of the lines indicate the onset and probable disappearance of symptoms of motion sickness. The onset of symptoms is indicated fairly accurately. The disappearance of symptoms, however, involves first a loss of susceptibility to the eliciting stimulus, then spontaneous restoration through homeostatic mechanisms and finally something termed convalescence, hence "disappearance" of motion sickness symptoms is difficult to determine. The vertical lines indicate when an antimotion sickness drug was taken and its composition. The administration of drugs increases the difficulty of diagnosing motion sickness, hence accuracy in diagnosis is greater in the absence of drug effects.

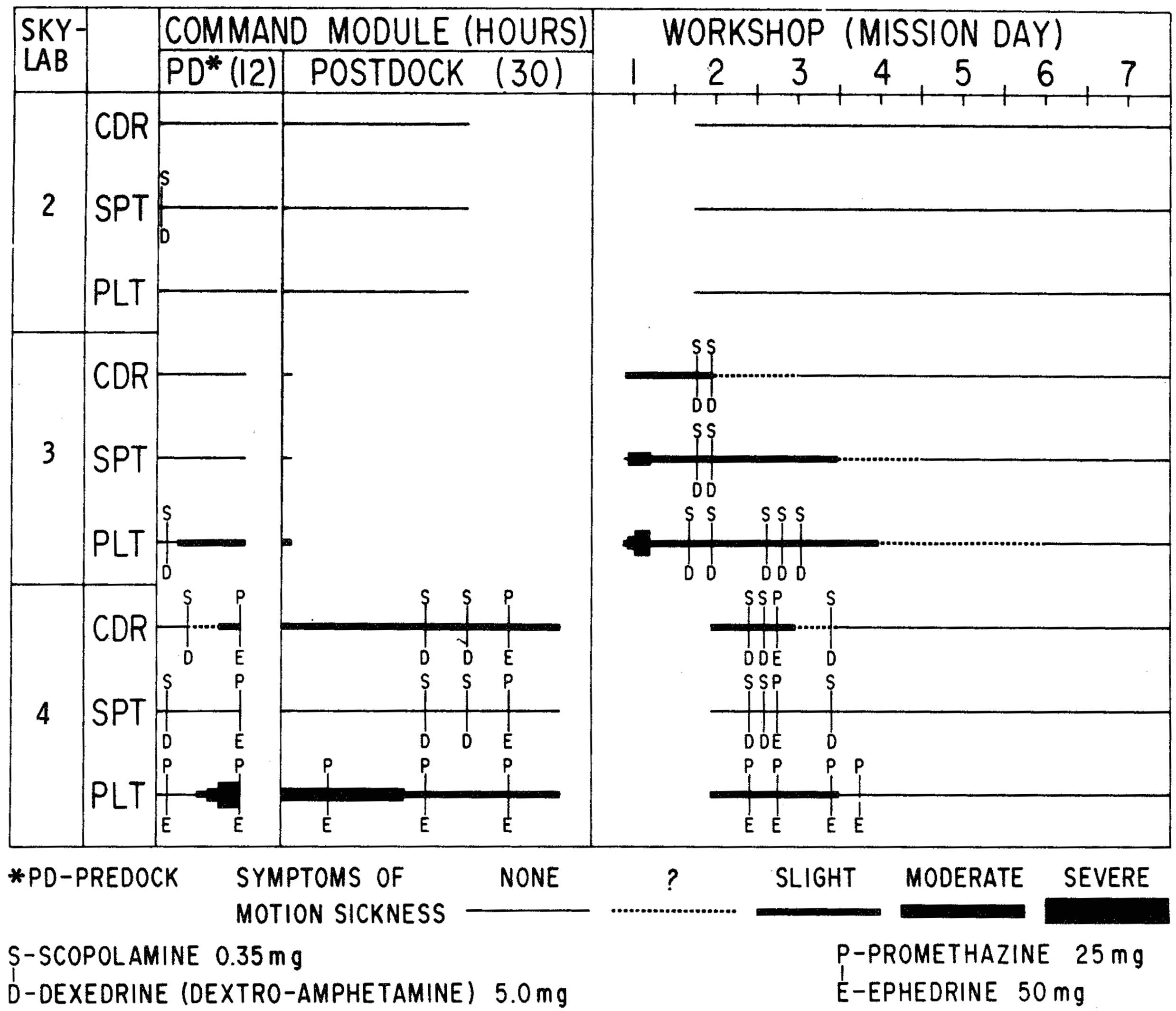

Figure I-4. Motion sickness under operational conditions.

Skylab 2. As indicated earlier, the Commander was, in all likelihood the least susceptible to motion sickness among the nine Skylab astronauts. He didn't take any antimotion sickness drugs and was symptom free under all conditions.

The Scientist Pilot, in a debriefing, stated, "I took the one 'scop/dex' (antimotion sickness drug) right after insertion (into orbit) that I had preprogramed myself to take, whether I needed it or not." He further stated. "I felt that, although we had no overt symptoms of motion sickness or any other specific syndrome related to transitioning to weightlessness, my appetite was a little bit less, neglecting day 1 when it was completely normal, and that it was a little less for somewhere like the first week. I don't know why this is. As I said, I had no particular symptoms. I felt fine during those first seven days, but I thought I felt even better after that."

It is also noteworthy that both the Commander and Scientist Pilot reported that while engaged in spinning rapidly about their long axes or "running" around the inside of the workshop, they experienced immediate reflex vestibular side effects, mainly "false sensations" of rotation. Based on past experience, both astronauts expected that motion sickness would follow the reflex effects and were surprised by their immunity.

The Skylab 2 Pilot did not take an antimotion sickness drug aloft and remained symptom free. Unlike his comrades, however, although he was aware of illusory phenomena their intensities made little impression on him.

During entry the Skylab 2 astronauts did not perceive the oculogravic illusion. The Scientist Pilot stated afterward, "I never picked it up at all. I think it just had to do with the fact that you have so many visual cues and you're so well lighted and also your attention is so riveted on the instruments that you have no such illusion * * *. The first time we were conscious of any vestibular inputs was after we were on the water and unstrapped and moved from the couch. There was nothing at all during the entry." The Skylab 2 Commander stated, "My first head movement was when I was unstrapped and on the water, when I rolled up on my right and moved around * * *. It was exactly what I would expect had I been riding the centrifuge and done the same thing." The Pilot stated, "And I did move. I got up from the couch and looked out the window for the ship while we were still on the chutes, and that didn't bother me."

At splashdown the sea state was 5, and the command module landed and remained upright. The astronauts were quite confident that they would not experience motion sickness on return and accordingly did not take antimotion sickness drugs prior to entry. Seasickness was not

experienced by the Commander but severe symptoms were manifested by the Scientist Pilot and mild symptoms by the Pilot.

Skylab 3. The Skylab 3 astronauts were quite confident before their mission that they would not become motion sick in weightlessness and did not take antimotion sickness drugs as a preventive measure.

The Pilot experienced mild symptoms of motion sickness within an hour after insertion into orbit. During launch he wore a space suit and helmet (as did the other crewmen). He was not aware of any illusory phenomena on transiton into zero gravity. Shortly after transition he removed his helmet and soon thereafter his space suit. It was in close relation to taking off the suit that the first symptoms of motion sickness were experienced. He took an antimotion sickness capsule that relieved his symptoms for a few hours. Later, symptoms returned and he restricted his activities; he deliberately avoided, however, taking another antimotion sickness capsule while based in the command module.

During the activation of the workshop, about 11 hours into the flight, the Commander and Scientist Pilot also reported the onset of motion sickness. Shortly thereafter the Skylab 3 Scientist Pilot vomited. For three days the astronauts experienced symptoms of motion sickness which were intensified by movement and alleviated after taking the drug or restricting their movements. During this period their workload was lightened.

On mission day 2 the Scientist Pilot executed standardized head movements for 30 minutes with the object of increasing his rate of adaptation. With eyes closed he had "no difficulty", but with eyes open he experienced "developing malaise".

On mission day 4 regular working hours were resumed, although some degree of susceptibility to motion sickness remained in all three astronauts. Recovery was complete by the seventh mission day.

Prior to splashdown the antimotion sickness drugs were taken, and symptoms were prevented even though the sea state was twice as severe as that to which the Skylab 2 crew had been exposed. On both days at sea aboard the carrier, the Pilot took an antimotion sickness capsule, implying some susceptibility to sea sickness.

Skylab 4. In the light of Skylab 2 and Skylab 3 findings, the Skylab 4 crew was scheduled to take antimotion sickness drugs through mission day 3 and, thereafter, as required. The drugs actually administered are shown in table I-V. The drugs were referred to as "uppers" (A) and "downers" (B) and on mission day 8 the Scientist Pilot took the drug combination B as a soporific rather than for its antimotion sickness properties. Prior to entering the workshop the Pilot experienced nausea and vomiting and was not free of symptoms during the first three

days. The Commander reported "epigastric awareness" prior to meals which may have represented susceptibility to motion sickness, and the Scientist Pilot was symptom free. It is interesting that all crewmen took antimotion sickness drugs during recovery at sea and were symptom free.

TABLE I-V

SKYLAB ANTIMOTION SICKNESS MEDICATION

MISSION EVENT	APPROX TIME (HOURS c.s.t.)	Commander	Scientist Pilot	Pilot
LAUNCH DAY (MD 1)				
AFTER INSERTION	0900		A	B
AFTER NC-1*	1100	A		
AFTER DOCKING	1700	B	B	B
	2300			B
MD-2 & MD-3	0600	A	A	B
ON ARISING	1000	A	A	
	1400	B	B	B
MD-4	0600	A	A	B
ON ARISING	1400			B
MD-8	BEDTIME		B	
MD-33	BEDTIME		B	
MD-82	BEDTIME		B	
MD-84 ABOUT 2 HOURS PRIOR TO SPLASH (ENTRY)		A	A	A

A SCOPOLAMINE / DEXEDRINE (0.35/5.0 mg)
B PROMETHAZINE / EPHEDRINE (25/50 mg)
* FIRST PHASING MANEUVERS

Experimental Conditions

Skylab 2. The findings in figure I-5 demonstrate that the Scientist Pilot and Pilot (the Commander did not participate) were less susceptible to motion sickness when they executed head movements during rotation aloft than when they did so on the ground. Preflight, on three widely separated occasions, the M II A endpoint was consistently elicited after 30 to 60 head movements while those astronauts were being rotated at 12.5 rpm (Scientist Pilot) or 15 rpm (Pilot). When rotation tests were carried out in the workshop, both of these astronauts were virtually symptom free; their minimal responses, which were transient, did not even qualify for a score of one point. This was true even when the angular velocities were increased (in two steps) to 30 rpm. The ephemeral manifestation reported by the Scientist Pilot on mission day 20 was a slight increase in subjective body warmth, and on mission day 24, a mild cold sweating. The temporary manifestations reported by the Pilot on mission day 6 when the rotating litter chair was stationary were epigastric awareness and increased body warmth; and, on mission day 24, slight dizziness and cold sweating.

Postflight there was no significant change in the susceptibility of the Scientist Pilot to motion sickness compared with preflight, and, for the Pilot, no significant change on the third day postflight. The decrease in susceptibility manifested by the Pilot on day 8 postflight does not, in all likelihood, reflect more than a temporary change in his susceptibility.

Skylab 3. The findings in the three astronauts are summarized in figure I-6. It can be seen that they were virtually immune to experimental motion sickness aloft and that their susceptibility was lower, at least temporarily, after the mission than before.

The Commander was tested in the rotating litter chair on two widely separated occasions preflight and demonstrated similar susceptibility levels each time. On mission days 26 and 41 he was symptom free when rotated clockwise, respectively, at 20 and 30 rpm. On mission day 52 he was rotated counterclockwise at 30 rpm and experienced what he described as a slight vague "malaise" that persisted for approximately 30 minutes following the test. The question arises whether secondary etiological factors accounted for both the appearance and nature of this symptom, which is not typical of acute motion sickness, or whether the astronaut was not quite adapted to counterclockwise rotation. Postflight, the Commander was symptom free on the day after recovery when he executed head movements with the rotating litter chair stationary and on the second day postflight when it was rotating clockwise at 15 rpm. On the fifth day postflight an endpoint was reached that approximated his preflight susceptibility level.

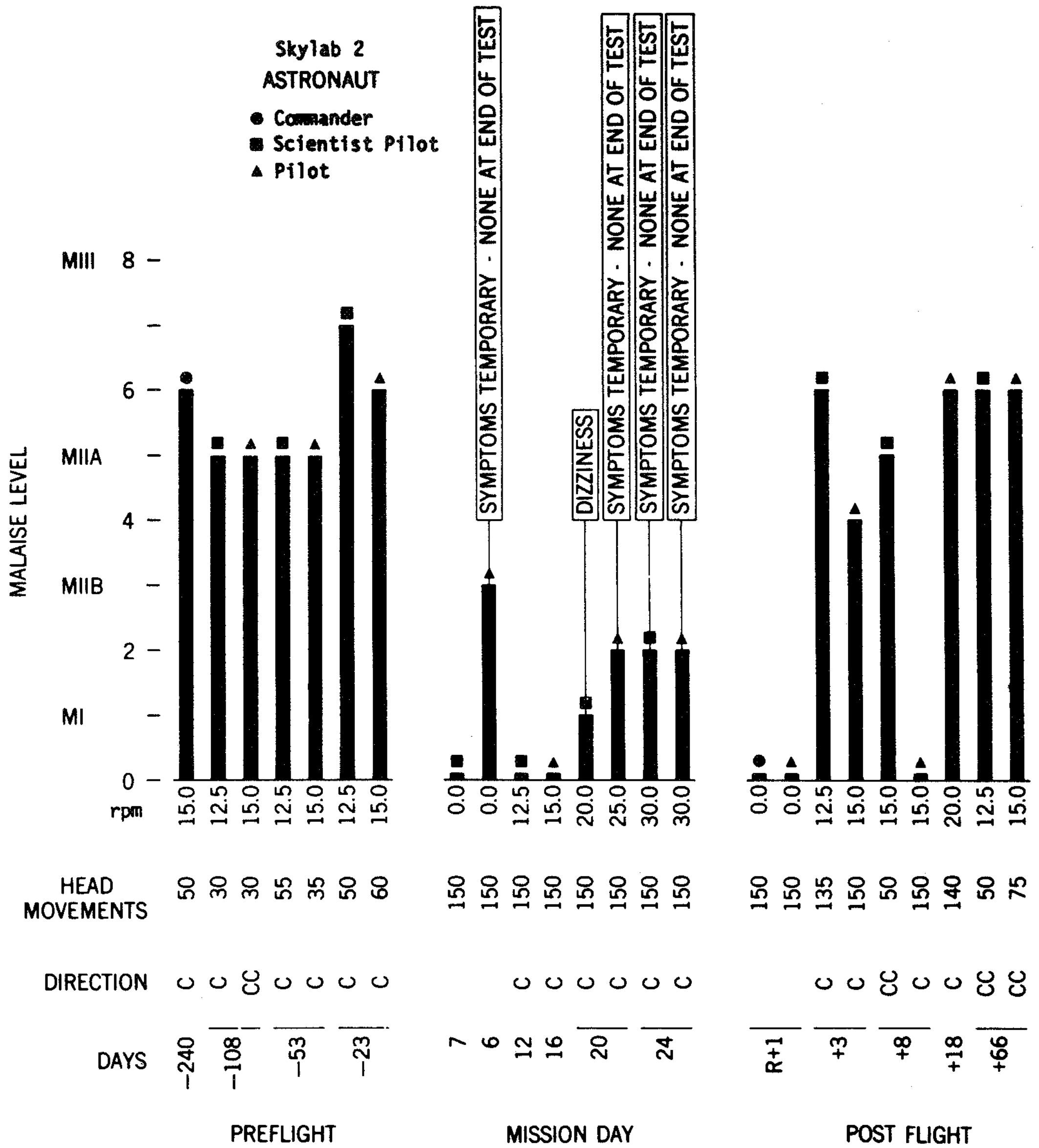

Figure I-5. Motion sickness symptomatology on Skylab 2 astronauts quantitatively expressed in terms of malaise level, as evoked by the test parameters (rotational velocity, number of head movements, and direction of rotation) used before, during, and after the Skylab 2 mission.

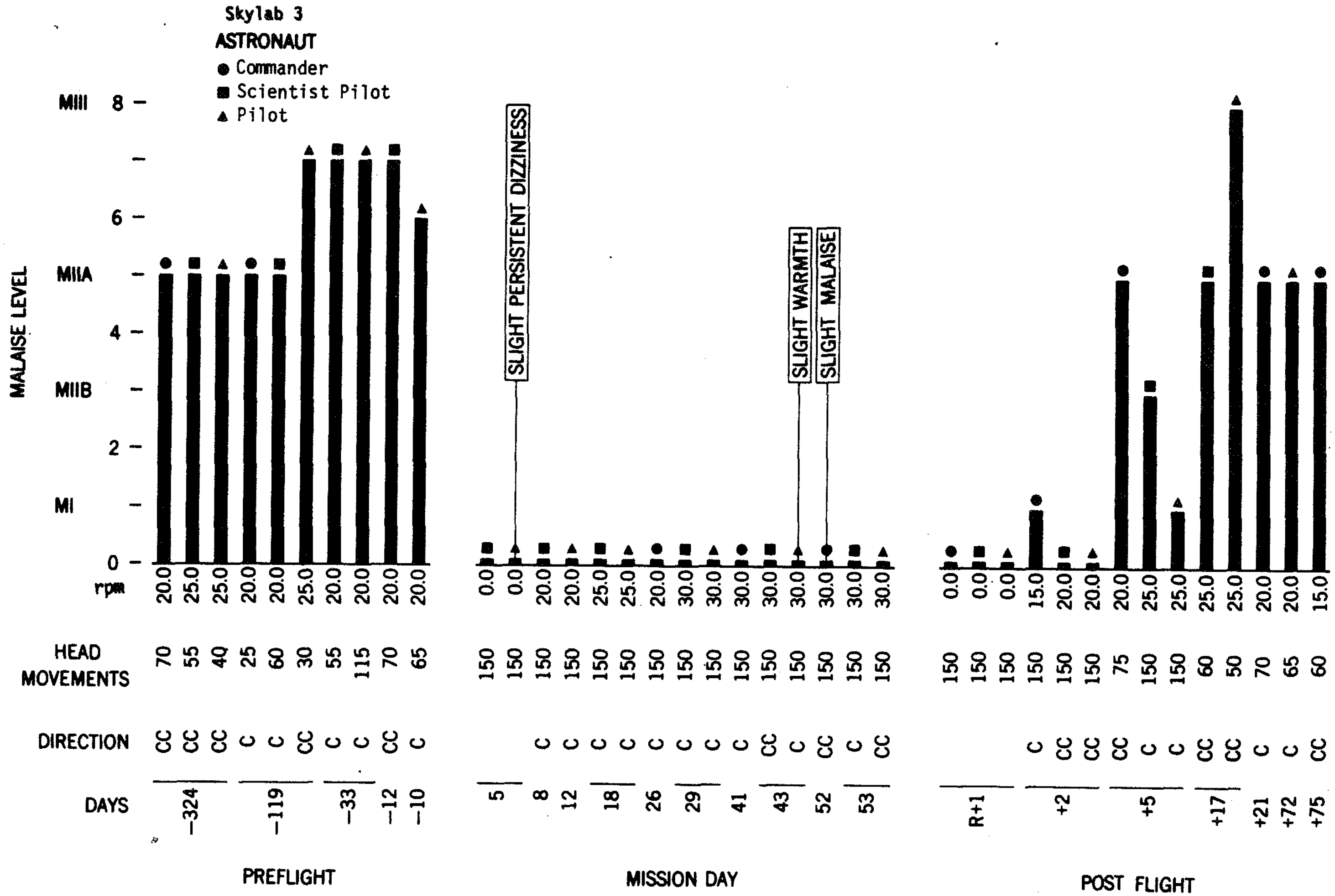

Figure I-6. Motion sickness symptomatology of Skylab 3 astronauts quantitatively expressed in terms of malaise level as evoked by the test parameters (rotational velocity, number of head movements, and direction of rotation) used before, during, and after the Skylab 3 mission.

The Scientist Pilot was tested on four widely separated occasions preflight, and the M II A endpoint was always reached with approximately the same stressor stimulus. Aloft the Scientist Pilot was tested on six occasions, the first on mission day 5 with the rotating litter chair stationary. Thereafter, the angular velocities of the chair, beginning at 20 rpm, were increased to 25 rpm, then to 30 rpm for the last three tests; symptoms of motion sickness were never elicited. Postflight he was symptom free on the day after recovery when the rotating litter chair was stationary and again on day 2 postflight when the rotating litter chair was rotating counterclockwise at 20 rpm. On day 5 postflight the Scientist Pilot experienced very mild symptoms (dizziness II, drowsiness I), but an endpoint was not reached when the rotating litter chair was rotating clockwise at 25 rpm. The M II A endpoint was reached on day 17 postflight with the rotating litter chair rotating counterclockwise. The Skylab 3 Pilot was tested on four widely separated occasions preflight and demonstrated similar test scores on all four occasions. Aloft he was tested on six occasions. On mission day 5 he experienced slight but persistent "dizziness" when the rotating litter chair was stationary. (It will be recalled that on mission day 5 the Pilot was just getting over his susceptibility to motion sickness in the workshop and that he had taken an antimotion sickness drug on mission day 3). Thereafter, he was symptom free when rotated clockwise at 20, 25, and 30 rpm and on mission days 8, 18, and 29, respectively. On mission day 43 he experienced "some body warmth" that did not rate a one-point score (moderate intensity required) while rotating clockwise at 30 rpm, but he was symptom free ten days later while rotating counterclockwise at 30 rpm.

Skylab 4. The findings are summarized in figure I-7. Preflight the ceiling on the test was closely approached in the case of the Commander and Pilot and nearly reached in the case of the Scientist Pilot. In the workshop the ceiling of the test was quickly reached without eliciting any symptoms of motion sickness. In view of this immunity a change in the procedure was instituted. This change was essential to determine whether the absence of responses was the result of complete insusceptibility or, in part, the consequence of adaptation to the stressful accelerations during the period of exposure to rotation. The latter was tested by reversing the direction of rotation immediately after 150 head movements had been executed in the initial direction of rotation. The basis for this approach rested on the finding that although bidirectional adaptation effects are acquired with either clockwise or counterclockwise rotation, the level of adaptation is greater in the direction of turn than in the opposite direction. Therefore, by reversing the direction, the elicitation or nonelicitation of symptoms of motion sickness served to indicate,

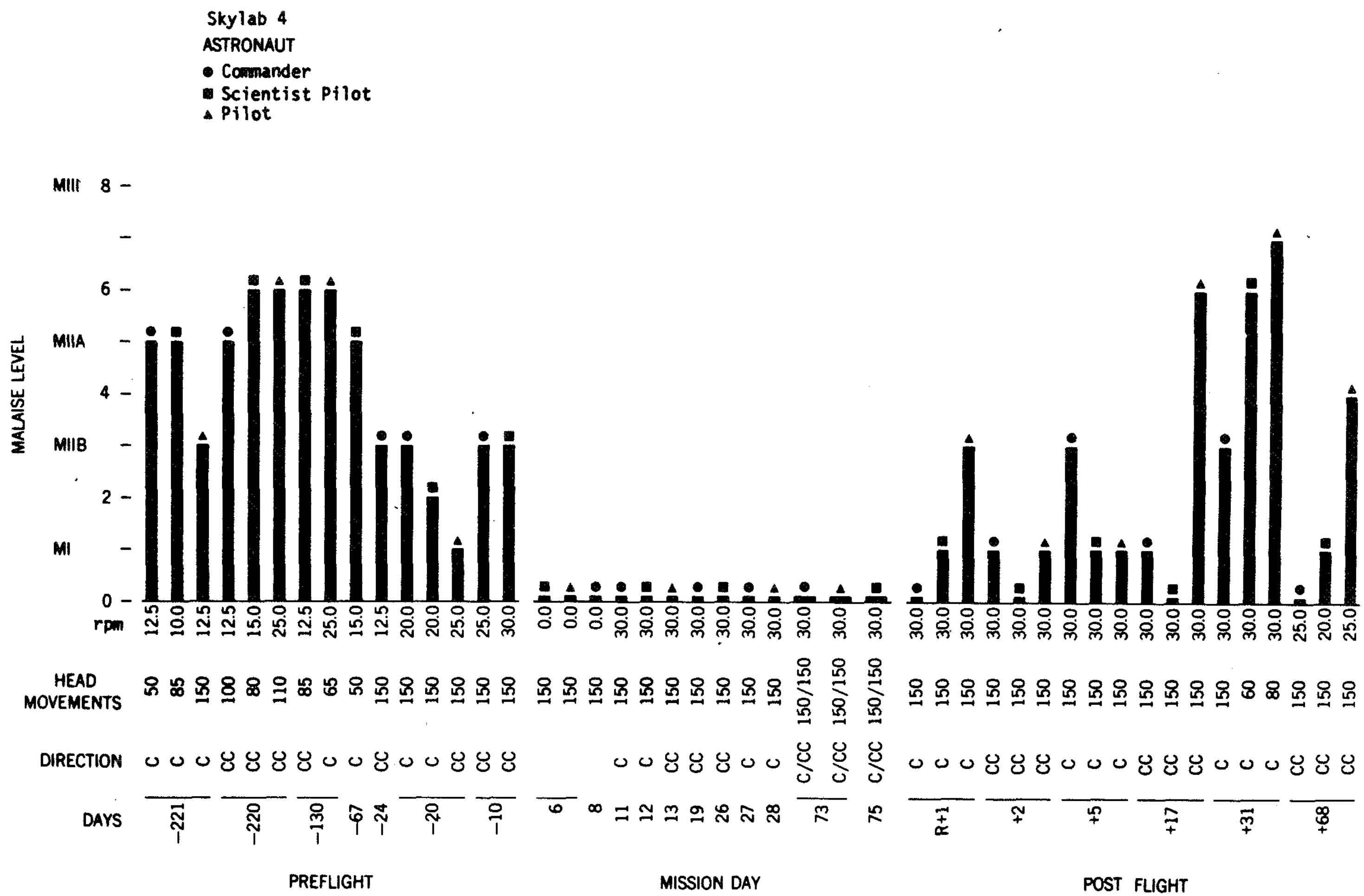

Figure I-7. Motion sickness symptomatology of Skylab 4 astronauts quantitatively expressed in terms of malaise level as evoked by the test parameters (rotational velocity, number of head movements, and direction of rotation) used before, during, and after the Skylab 4 mission.

respectively, whether the absence of symptoms during the initial direction of turn was or was not due in part to the acquisition of adaptation. On mission day 73, the Commander and Pilot, and on mission day 75, the Scientist Pilot remained symptomless during the bidirectional test procedure. Consequently, they were not adapting during the test.

Tests conducted postflight on days 1, 2 and 5 revealed either very mild symptoms or immunity; the motion sickness endpoint was not reached. On day 17 postflight the Pilot reached the motion sickness endpoint. On day 31 postflight both the Pilot and Scientist Pilot reached endpoints and the Commander scored 3 points. On day 68 postflight the rpm were reduced to 25 rpm and none reached the motion sickness endpoints.

Discussion

There were clear-cut findings under operational and experimental stimulus conditions that will serve as points of departure in the following discussion.

Operational Conditions

Command Module. Two astronauts were motion sick when based in the command module, the Skylab 3 Pilot and the Skylab 4 Pilot. The latter had taken two doses of an antimotion sickness drug (Promethazine HCl 25 milligrams and ephedrine sulfate 50 milligrams) in 8 hours, which may have complicated the symptomatology, hence, the attention here will center on the Skylab 3 Pilot.

Shortly after transition into orbit the Skylab 3 Pilot experienced mild symptoms characteristic of motion sickness. The close temporal relation between the astronaut's activities and the onset or alleviation of symptoms and the relief following administration of the antimotion sickness capsule confirmed the diagnosis, the earliest confirmation among space crewmen on record.

On entry into weightlessness few of the internal adjustments that were initiated during the transition were complete. Alterations such as in hemodynamic adjustments, redistribution of body fluids, and changes in electrolyte balance that might affect susceptibility to motion sickness, either via the vestibular system or more indirectly, were at various stages along their time course (25-29). Even though the stimulus to the macular receptors due to gravity was lost, the question had arisen as to whether the physiological deafferentation process had stabilized.

Loss of the g-load would affect the "modulating influence" of the otolithic system. If the otolithic influence was inhibitory the responses elicited by stimulation of the canals are said to be "exaggerated" (30). The observations bearing on this point in parabolic flight, however, indicated reduced responses to canalicular stimulation (31-33) during the weightless phase.

Fortunately, in the case of the Skylab 3 Pilot, it was possible to follow his course which demonstrated that there was little or no support for the notion that nonvestibular predisposing factors in addition to the immediate eliciting factors were involved; he remained motion sick or susceptible to motion sickness at least through mission day 3 and probably two days longer. Moreover, the fact that the remaining seven astronauts did not have motion sickness while based in the command module argues against a common unique etiological factor.

Workshop. Under operational conditions three astronauts were motion sick for the first time aloft after making the transition from the command module into the workshop, implying that stimulus conditions were more stressful then than at any time in the command module and that the adaptation acquired in the command module offered inadequate protection in the workshop.

The spaciousness of the workshop provided the greatest opportunity up to the present time to reveal the great potentialities in weightlessness for limiting natural movements and encouraging highly unnatural movements that often resembled acrobatic feats. Movies of the astronauts carrying out their tasks in the workshop, often involving transitions from one place to another, best display the relatively large component of passive movement associated with active movements, with the opportunities for generating unusual patterns of vestibular stimulation and unusual or abnormal visual inputs.

The Skylab 3 Commander and Scientist Pilot began to have symptoms shortly after entering the workshop, and soon thereafter the Pilot vomited. The question has been raised whether the motion sickness experienced by the Pilot influenced unfavorably the elicitation of symptoms in the other two crew members. This seems unlikely for two reasons, namely, the Pilot had been motion sick (or highly susceptible to motion sickness) since the first hour in flight, and symptoms appeared in the Scientist Pilot and Commander before the Pilot vomited. Among these three astronauts under workshop conditions, the Pilot was not only most susceptible but also susceptible for the longest period while the Commander was least susceptible with the shortest time course.

It was on mission day 2 that the Scientist Pilot executed standardized head movements for a short period and did not have any symptoms with eyes closed, but, continuing the head movements with eyes open, he did experience symptoms. Whether symptoms would have been elicited if the head movements had been continued with eyes closed is not known, but the visual inputs contributed to the interacting sensory stimuli and probably were of etiological significance. This brief "experiment" represented an attempt at programing the acquisition of adaptation effects and underscores the possible advantage of "eyes closed" in the early stage of adaptation, something that has been demonstrated under laboratory conditions (34). After the third or fourth day it is difficult to sort out the countervailing influences of eliciting and restoring mechanisms, upon which were superimposed the nonspecific general effects of a period of ill health. It is especially noteworthy that recovery was not complete until mission day 7.

The Skylab 4 Commander despite the administration of antimotion sickness drugs 3 times daily on mission days 2 and 3 became mildly motion sick, and the Pilot continued, despite medication, to demonstrate, on occasion, symptoms of motion sickness.

There is much resemblance between the time course of the symptomatology of motion sickness elicited in the workshop and in a slow rotation room. This resemblance is due in large part to the etiological realtion between "activities" and eliciting stimuli. The two environments have, in common, the generation of stressful stimuli when a person is engaged in various activities and abolition of the stressful stimuli when the head and body are fixed. In both environments there are:

° a delay in appearance of symptoms after the onset of the stressful stimuli,

° a gradual or rapid increase in severity of symptoms,

° modulation by secondary influences,

° perseveration for a time after sudden cessation of stimuli, and

° a response decline, indicating that restoration is taking place spontaneously through homeostatic events and processes.

If the intensity of the stimuli is high, the latencies associated with the appearance and disappearance of symptoms will be brief. With the acquisition of adaptation effects and concomitant reduction in the intensity of the stimuli, the latencies are increased, and, characteristically, restoration may not only be prolonged but also complicated by

the appearance of symptoms not typical of acute motion sickness. Thus, in a slow rotation room it has been demonstrated that drowsiness may be elicited in the virtual absence of other symptoms (35) and that after the nausea syndrome has disappeared, drowsiness, lethargy, and fatigue remained (36).

An analysis of the foregoing and similar manifestations has led to the definition of a unique syndrome. For clarity, it is termed the Sopite syndrome (from the Latin Sopor, meaning drooping or drowsy) (Graybiel, A. and J. C. Knepton, "The Sopite syndrome: a component or even sole expression of motion sickness symptomatology", in preparation). This syndrome may be part of the clinical symptomatology or, if the eliciting stimuli are at a critical level of intensity, it may be the sole manifestation. In addition to drowsiness and lethargy, there is a reduced interest in ongoing events and a performance decrement, especially when attempting to carry out tasks involving high-level mental activity. Lastly, just as in recovering from any illness, there is a period termed "convalescence". It is possible that the Skylab 2 Scientist Pilot experienced something in the nature of the Sopite syndrome in the workshop.

Under *experimental conditions* in the workshop the virtual failure to elicit symptoms of motion sickness in any of the five astronauts who were exposed to a stressful type of accelerative stimuli in a rotating chair (on or after mission day 8) implies that, under the stimulus conditions, susceptibility was lower aloft than on the ground, where symptoms were elicited preflight and postflight. The amount of this decrease in susceptibility could not be measured because the "ceiling" on the test (30 rpm) was so quickly reached.

The difference in susceptibility between workshop and terrestrial conditions is readily traced to gravireceptors (mainly in the otolith organs; touch, pressure and kinesthetic receptor systems possibly contributing) for the reason that stimulation of the canals was the same aloft as on the ground, and visual inputs were always excluded. If it is assumed that the otolith system is responsible, then the absence of stimulation to the otolithic receptors due to gravity must have a greater influence (tending to reduce the vestibular disturbance) than the disturbing influences of the transient centrifugal linear and Coriolis accelerations generated when head and trunk movements were executed in the rotating litter chair. Although these transient accelerative forces, as pointed out in the section on Procedure, are substantial their effectiveness as stimuli are virtually unknown. The otolithic zonal membrane has considerable mass, and transient accelerations lasting fractions of a second might have little or no effect.

The absence of gravity, causing what has been termed "physiological deafferentation" of the otolith receptor system, would be expected to reduce not only the indirect modulating influence of the otolithic system on the canalicular system but also its opportunity to interact directly with this system.

The important question arises whether the prior adaptation to weightlessness "transferred" to the rotating environment or whether it played a secondary role; namely, simply ensuring the absence of overt as well as any covert symptoms of motion sickness. In this connection, the findings in parabolic flight are pertinent, inasmuch as the periods of exposure to near-weightlessness are brief. The alternating periods of supragravity and subgravity states in parabolic flight create a bias in favor of increased susceptibility to motion sickness in the rotating litter chair. Motion sickness susceptibility has been compared in 74 healthy subjects who executed standardized head movements while they rotated at constant velocity during sequential weightless phases of parabolic flights and during periods of exposures under laboratory conditions (12). Most subjects demonstrated either a substantial increase or decrease in susceptibility, while a few experienced little change in susceptibility.

Conclusions and Recommendations

° Skylab findings indicate three ways or means that permit weightlessness, a static state, to qualify as a unique motion environment: first , its quasidynamic potentialities for inducing changes in nonrigid parts of the body; second, its unique potentialities at once limiting a person's natural movements and encouraging unnatural movements that may result in unusual vestibular and visual sensory inputs; third, the demonstration under specific experimental conditions that susceptibility is lower aloft than on the ground.

° The lower susceptibility to vestibular stimulation aloft, compared with that on the ground under experimental conditions, was "traced" to the reduction in g-load but had to meet a precondition, namely, either there was no need to adapt, or, as exemplified by the Skylab 3 Pilot, adaptation to weightlessness had been achieved. The inference is that from the standpoint of the vestibular organs, the "basic" susceptibility to motion sickness is lower in weightlessness than under terrestrial conditions; how much lower remains to be measured.

° In the case of the Skylab 3 Pilot, the prolonged period of susceptibility would seem to rule out any short-lived etiological factors associated with entry into orbit.

- In the workshop three astronauts experienced motion sickness for the first time aloft, thus inferring at once the more stressful conditions in the workshop compared with those in the command module and the inadequate level of adaptation previously acquired.

- None of the Skylab 2 crewmen experienced motion sickness in the workshop, implying either there was no need to adapt (a possibility in the case of the Commander) or that prior adaptation in a less stressful environment afforded adequate protection. The period during which the "adequate" adaptation in the command module was acquired by the Skylab 2 crewmen was much shorter than the period during which Skylab 3 and Skylab 4 crewmen were motion sick, let alone the additional period while recovering from motion sickness. Both of these findings have implications that argue for programing the acquisition of adaptative effects.

- Findings in some of the astronauts, under both operational and experimental conditions, emphasized the distinction between two categories of vestibular side effects, namely, immediate reflex phenomena (illusions, sensations of turning, *et cetera*) and delayed epiphenomena that include the constellation of symptoms and syndromes comprising motion sickness. The relationship between the two categories deserves further study.

- The drug combinations l-scopolamine and d-amphetamine and promethazine hydrochloride and ephedrine sulfate were effective in prevention and treatment of motion sickness; nonetheless, they are not the "ideal" antimotion sickness drugs.

- Although not used as a diagnostic test the antimotion sickness drug was helpful in diagnosing motion sickness, notably in the case of the Skylab 3 Pilot.

- Prevention of motion sickness in any stressful motion environment involves selection, adaptation, and the use of drugs. Today we lack laboratory tests that accurately predict susceptibility to motion sickness in weightlessness; susceptibility to motion sickness in the weightless phase of parabolic flight is promising but has not been validated.

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II. THRESHOLDS FOR PERCEPTION OF ANGULAR ACCELERATION AS REVEALED BY THE OCULOGYRAL ILLUSION (PRELIMINARY RESULTS)

ABSTRACT

The oculogyral illusion, briefly defined, is the apparent movement (in the direction of turn) of visual objects that are fixed relative to an observer who is passively exposed to angular acceleration. The purpose of the present study was to measure the oculogyral illusion response patterns of eight astronauts as determined on several occasions in the workshop and to compare them with measurements made preflight and postflight. The results show that aloft none of the subjects registered a consistent improvement in performance; compared with ground-based values, four showed no change and four a slight decrement. The results are discussed in terms of experimental circumstances in the workshop aloft and on the ground and in terms of underlying mechanisms.

INTRODUCTION

Both the oculogyral illusion and ocular nystagmus are used as indicators of semicircular canal function and behavior. Nystagmography, generally regarded as the most useful of all indicators of vestibular function, was not available. In consequence, we made use of the oculogyral illusion (1) which, whatever its drawbacks, is a more sensitive indicator than nystagmus (2). The relation between the oculogyral illusion and nystagmus has long been an object of interest (3-5), and, while it seems that the illusion can be a consequence of nystagmoid movement, the behavior of the two responses may not only differ but even may simultaneously occur in the opposite sense.

Although complete agreement regarding the effect of g-loading on nystagmus may be lacking, the weight of the evidence indicates that the intensity of the nystagmic responses increases and decreases, respectively, with increases and decreases in g-load (6, 7). It is also to be noted that these effects are quickly manifested and are ascribed to otolithic exaltatory or inhibitory influences.

John Glenn conducted the first experiment in space flight that involved the oculogyral illusion (8). He compared the oculogyral illusion observed during rotation in the laboratory and in the Mercury spacecraft during the course of his orbital flight. In Glenn's opinion, the illusory effects as the result of very similar angular accelerations were "essentially the same".

Roman, *et al.* (9), used the oculogyral illusion to measure "the sensitivity of the semicircular canals to stimulation" during periods of weightlessness averaging 46 seconds in parabolic flight. This was accomplished by rolling the aircraft during periods of subgravity as well as during one-g control maneuvers and by timing the duration of apparent rotation of a visual target. It was concluded that there was no significant difference between the duration of the illusion under the two stimulus conditions.

PROCEDURE

Subjects

Eight of the nine Skylab astronauts (the Skylab 2 Commander did not participate) acted as test subjects. Each had demonstrated normal otolithic and semicircular canal function, as indicated, respectively, by ocular counterrolling, and by caloric as well as oculogyral illusion responses. The oculogyral illusion perception threshold of each participant measured initially by a method (10) different from the one used in this study fell within the lower half of the distribution of 300 similarly tested normal healthy males as shown in figure II-1.

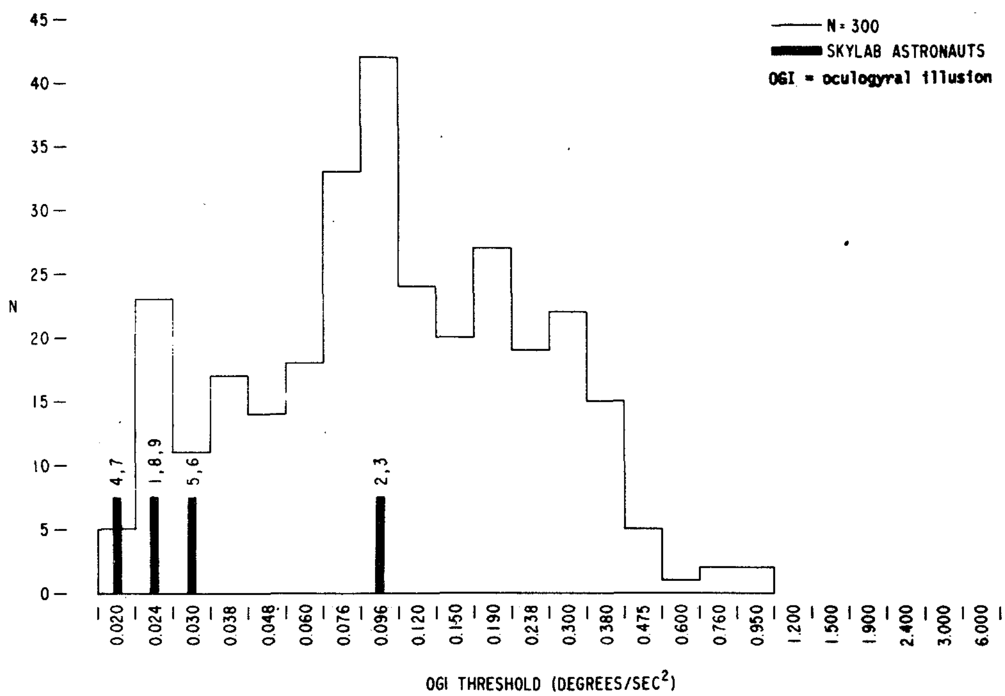

Figure II-1. Performance of the astronauts compared with that of 300 normal subjects using a variation of the Skylab procedure.

Apparatus

Vestibular Test Goggle. The vestibular test goggle, described in detail elsewhere (10), is a self-contained device worn over the subject's eyes (fig. II-2). The collimated line-of-light target, the only thing visible to the subject, is self-illuminated by a radioactive source and arbitrarily placed for viewing by the right eye only. The device is held on the face by its attachment to a biteboard assembly which, in turn, is secured by an adjustable support connected to the rotating litter chair. The distance between the ocular and occlusal planes is adjusted so that the subject's visual axis in its primary position is essentially in the "horizontal" plane containing the optic axis of the target system.

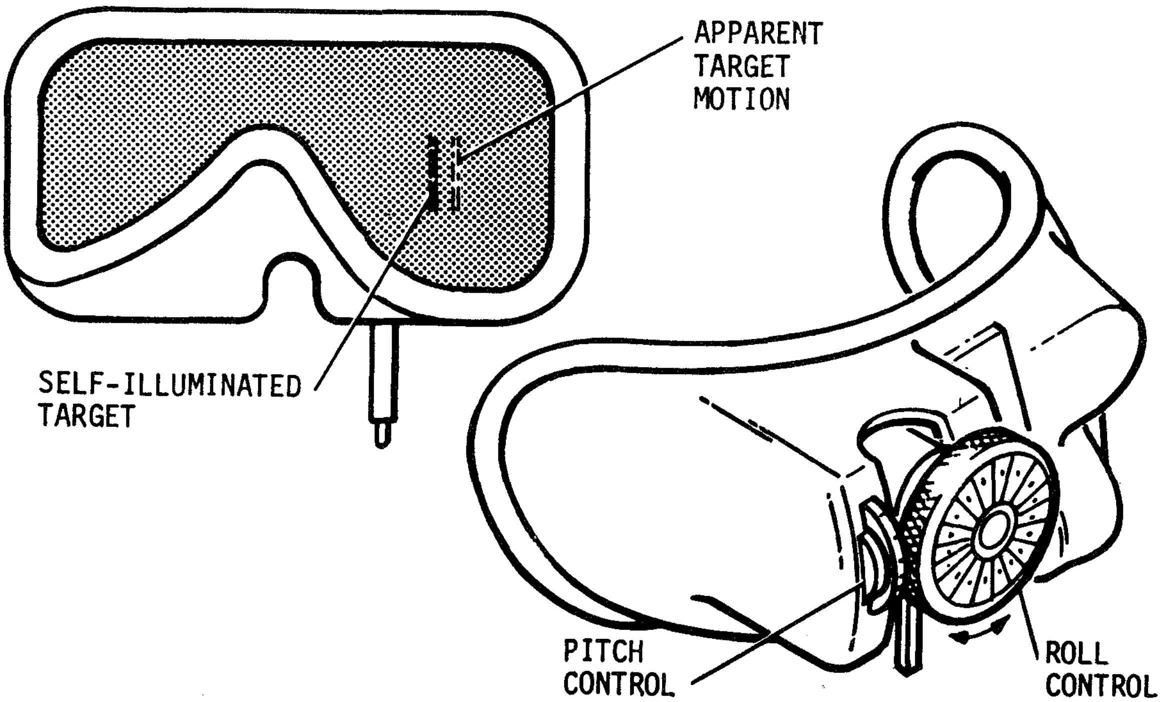

Figure II-2. Sketch of goggle device with slight rightward apparent displacement of line target as viewed by the astronaut. Some apparent displacement is commonly associated with apparent movement.

Acceleration Profile. The rotating litter chair, described in part 1, was programed to rotate a seated subject (clockwise or counterclockwise) at any one of 24 progressive logarithmic steps in velocity versus constant time (90 seconds) profiles within extremely narrow limits of precision. The man-supporting superstructure and motor of the rotating litter chair are directly coupled to eliminate gear slack and perceptible vibration and therefore meet the physiological requirement of eliminating small performance errors that are normally within the sensitivity range of the delicate vestibular organs.

Plan

The subject was secured in a seated postion within the rotating litter chair, and his biteboard and the vestibular test goggles were affixed to the support mechanism of the chair. He engaged the biteboard with his teeth and donned the vestibular test goggle by tilting his head forward 20°. The target viewed by his right eye was adjusted so that it appeared vertical and straight ahead. The purpose of the fixed head tilt was to place the "plane" of the lateral canals closer to the plane of rotation. The rotating litter chair device had the capability of generating any one of 24 progressive logarithmic steps of constant acceleration ranging from $0.02°/sec^2$ (step 1) to $3.00°/sec^2$ (step 23); two log units of acceleration separated steps 23 and 24. However, in order to reduce in-flight experimental time, the test selection was limited among steps 1, 4, 8, 10, 14 and 18. In the first two missions, steps 1, 4, 8, 10 and 18 were used; in the third mission, step 14 was introduced as a test option when appropriate to determine performance within the large interval between acceleration log steps 10 and 18. When step 14 was used, step 1 or 18 was omitted, the choice depending upon the pattern of prior test performance by the subject. Testing was always done in the ascending order to acceleration rates. After one of the acceleration rates was selected on the basis of the predetermined test schedule and prior subject performance, the program start switch of the rotating litter chair was pressed. After two seconds of constant positive acceleration, the subject was signalled to open his eyes; after five seconds' accumulative time, he was signalled again to judge whether the target appeared to move rightward or leftward, or to remain stationary. If the subject did not respond after 15 seconds' accumulative time, a third signal was given. If no response was received within 20 seconds' accumulative time, the end of the constant acceleration period and the beginning of the 25-second constant velocity phase, it was assumed and recorded that no movement was perceived. The subject was instructed to close his eyes immediately after each response.

The down ramp of the profile required the subject, as in postive acceleration, to open his eyes at 2 seconds and to respond between the 5th and 20th second after deceleration had begun. After reaching zero revolutions per minute, the rotating litter chair remained stationary for at least 25 seconds.

RESULTS

All data collected before, during and after the Skylab missions 2, 3 and 4 are presented in table II-1. The table lists the number of a) correct, b) incorrect with respect to the apparent direction of movement, and c) no movement responses divided by the total number of expected right and left responses at each level of acceleration tested in each session, preflight, in-flight (mission day) and postflight. A summary of these results are portrayed in figure II-3 as average "frequency of seeing" curves with percentage of correct responses among eight trials for each of the acceleration test steps under the three major test conditions: preflight, in-flight, postflight. Comparisons of the tabulated preflight data indicate similar individual response patterns with a tendency for each subject to improve with repetition of the test.

A relatively wide range of accelerations was employed to increase the probability that each participant's subthreshold to suprathreshold range of response would, in the event of even gross changes, be captured during each test session aloft. It was found that the pronounced changes occurred principally at acceleration levels that produced near threshold levels of the oculogyral illusion perception (*i.e.*, perception frequency in this study is complicated by the procedure used. Although each astronaut was instructed to always report any nonmovement of target, he knew as the result of his dual role as subject and examiner that only right or left responses were appropriate. If he failed to ignore or was influenced by his knowledge of the procedure, the test became a forced-choice situation and the chance factor was 50 percent; if he chose among the three responses the change factor was 33-1/3 percent. An illustration that a given set could influence perception of the oculogyral illusion is given in the comments of the Skylab 4 Commander when he said, "I close my eyes and I can * * * and it took me about three times as long to figure out that I was really rotating to the left. I think that had I been rotating to the right and been prejudiced I would have probably seen it very quickly. But it was rather interesting to see that I could prejudice myself and then it made it very difficult for me to figure out the real rotation. I had to - it is really best to think at all of rotation in either direction. I find out I might also add is that I saw quite a few white flashes - about seven - white flashes while I had the

TABLE II-I.

OCULOGYRAL ILLUSION RESPONSE FOR EIGHT ASTRONAUTS

Number of correct and incorrect responses divided by the total number of expected correct responses reported by eight Skylab astronauts (Skylab 2 Commander did not participate). When exposed to constant angular acceleration at indicated log step increases, preflight, in-flight, and postflight.

			Response				Response				Response				Response			
		Acc Level	Correct	Incorrect Left	Incorrect Right	Incorrect None	Correct	Incorrect Left	Incorrect Right	Incorrect None	Correct	Incorrect Left	Incorrect Right	Incorrect None	Correct	Incorrect Left	Incorrect Right	Incorrect None
Skylab 2 Scientist Pilot	Preflight		L-53*				L-23											
		1	2	0	1	5	3	1	0	4								
		4	2	1	0	5	2	0	1	5								
		8	3	0	1	4	3	0	0	5								
		10	7	0	1	0	8	0	0	0								
		14																
		18	8	0	0	0	6	0	0	0								
	In-Flight		MD 6†				MD 12				MD 20				MD 24			
		1	4	1	1	2	5	0	1	2	4	2	2	0	1	0	2	5
		4	3	0	0	5	6	0	0	2	1	1	2	4	4	0	0	4
		8	3	1	0	3	2	2	2	2	4	2	0	2	4	1	1	2
		10	3	1	2	2	6	1	0	1	7	0	0	1	7	0	1	0
		14																
		18	6	0	1	1	7	0	0	1	8	0	0	0	6	2	0	0
	Postflight		R + 3‡															
		1	3	0	0	5												
		4	1	1	0	6												
		8	4	1	1	2												
		10	7	1	0	0												
		14																
		18	8	0	0	0												
Skylab 2 Pilot	Preflight		L-53				L-22											
		1	1	1	0	6	2	1	0	5								
		4	7	0	0	1	0	1	0	7								
		8	6	1	1	0	4	2	2	0								
		10	8	0	0	0	7	0	0	1								
		14																
		18	8	0	0	0	8	0	0	0								
	In-Flight		MD 6				MD 16				MD 20				MD 24			
		1	2	2	1	3	1	0	0	7	1	0	0	7	4	1	2	1
		4	4	0	0	4	3	0	0	5	2	0	0	6	4	1	0	3
		8	2	0	0	6	1	1	2	4	1	0	1	6	3	0	1	2
		10	6	0	1	1	6	0	0	2	6	0	1	1	6	0	1	1
		14																
		18	8	0	0	0	8	0	0	0	8	0	0	0	8	0	0	0
	Postflight		R + 3															
		1	3	1	0	4												
		4	4	0	2	2												
		8	7	1	0	0												
		10	7	1	0	0												
		14																
		18	8	0	0	0												

*Launch minus "n" number of days
†Mission Day "n"
‡Recovery plus "n" number of days

TABLE II-I. (Continued)

Crewman	Phase	Acc Level	Response Correct	Incorrect Left	Incorrect Right	Incorrect None	Response Correct	Incorrect Left	Incorrect Right	Incorrect None	Response Correct	Incorrect Left	Incorrect Right	Incorrect None	Response Correct	Incorrect Left	Incorrect Right	Incorrect None	Response Correct	Incorrect Left	Incorrect Right	Incorrect None	Response Correct	Incorrect Left	Incorrect Right	Incorrect None
Skylab 3 Commander	Preflight		L-119 *																							
		1	5	2	1	0																				
		4	5	1	1	1																				
		8	4	3	1	0																				
		10	5	0	2	1																				
		14																								
		18	8	0	0	0																				
	In-Flight		MD 41 †				MD 52																			
		1	2	3	1	2	5	1	2	0																
		4	4	2	0	2	4	1	1	2																
		8	6	0	0	2	5	2	0	1																
		10	5	2	1	0	5	0	1	2																
		14																								
		18	6	2	0	0	8	0	0	0																
	Postflight		R + 4 ‡				R + 9																			
		1	4	4	0	0	5	3	0	0																
		4	4	4	0	0	4	2	1	1																
		8	5	2	1	0	6	1	1	0																
		10	4	4	0	0	4	2	1	1																
		14																								
		18	6	0	2	0	7	1	0	0																
Skylab 3 Scientist Pilot	Preflight		L-119				L-33				L-12															
		1	2	4	2	0	6	2	0	0	3	1	0	4												
		4	3	1	2	2	3	1	1	3	5	1	1	1												
		8	7	1	0	0	6	1	1	0	7	0	0	1												
		10	5	0	2	1	5	2	1	0	6	0	1	1												
		14																								
		18	7	0	0	1	7	0	0	1	8	0	0	0												
	In-Flight		MD 5				MD 12				MD 18				MD 29				MD 43				MD 53			
		1	3	3	2	0	4	1	1	2	5	1	2	0	4	2	2	0	4	1	1	2	6	1	1	0
		4	7	1	0	0	4	0	3	1	3	1	3	1	5	1	2	0	5	0	1	2	3	1	3	1
		8	5	0	2	1	3	1	2	2	3	3	2	0	2	1	4	1	4	1	2	1	4	1	2	1
		10	7	1	0	0	4	1	2	1	8	0	0	0	6	1	0	1	6	0	1	1	4	2	1	1
		14																								
		18	8	0	0	0	8	0	0	0	8	0	0	0	8	0	0	0	7	0	1	0	7	0	0	1
	Postflight		R+4				R+9																			
		1	5	1	1	1	6	2	0	0																
		4	4	1	2	1	4	2	2	0																
		8	6	1	1	0	8	0	0	0																
		10	7	0	1	0	6	0	1	1																
		14																								
		18	8	0	0	0	8	0	0	0																
Skylab 3 Pilot	Preflight		L-119				L-33				L-10															
		1	0	3	1	4	4	1	2	1	3	2	2	1												
		4	2	2	2	2	3	0	1	4	2	1	1	4												
		8	2	3	3	0	3	0	1	4	5	0	1	2												
		10	5	0	0	3	6	0	1	1	6	0	1	1												
		14																								
		18	8	0	0	0	8	0	0	0	8	0	0	0												
	In-Flight		MD 5				MD 8				MD 18				MD 32				MD 43				MD 53			
		1	6	0	1	1	3	1	3	1	2	0	3	3	6	1	1	0	4	2	1	1	2	2	3	1
		4	3	0	2	3	6	1	1	0	2	1	1	4	4	1	2	1	5	1	0	2	4	1	2	1
		8	5	0	0	3	4	0	2	2	3	0	2	3	3	2	2	1	7	1	0	0	6	1	0	1
		10	5	0	0	3	4	1	2	1	5	0	1	2	7	0	0	1	6	1	0	1	5	1	0	2
		14																								
		18	8	0	0	0	8	0	0	0	7	0	0	1	8	0	0	0	8	0	0	0	6	1	1	0
	Postflight		R + 4				R + 9																			
		1	7	0	0	1	4	2	2	0																
		4	3	2	2	1	4	2	2	0																
		8	3	2	2	1	5	2	1	0																
		10	6	1	1	0	5	1	2	0																
		14																								
		18	8	0	0	0	8	0	0	0																

* Launch minus "n" number of days
† Mission Day "n"
‡ Recovery plus "n" number of days

TABLE II-I. (Concluded)

			Response				Response				Response				Response				Response				Response			
		Acc Level	Correct	Incorrect Left	Incorrect Right	Incorrect None	Correct	Incorrect Left	Incorrect Right	Incorrect None	Correct	Incorrect Left	Incorrect Right	Incorrect None	Correct	Incorrect Left	Incorrect Right	Incorrect None	Correct	Incorrect Left	Incorrect Right	Incorrect None	Correct	Incorrect Left	Incorrect Right	Incorrect None
Skylab 4 Commander	Preflight		L-219 *				L-24				L-20				L-10											
		1	4	2	1	1	6	1	1	0																
		4	6	0	1	1	5	0	1	2	7	0	1	0	7	1	0	0								
		8	7	0	1	0	6	1	1	0	7	0	0	1	7	0	1	0								
		10	6	0	1	1	8	0	0	0	8	0	0	0	8	0	0	0								
		14									8	0	0	0	7	0	1	0								
		18	8	0	0	0	8	0	0	0					8	0	0	0								
	In-Flight		MD 8 †				MD 11				MD 19				MD 27				MD 47				MD 60			
		1													3	3	2	0	2	3	3	0	5	1	2	0
		4	1	4	3	0	5	1	1	1	4	2	2	0	5	1	2	0	4	2	2	0	5	1	1	0
		8	6	1	1	0	7	0	1	0	6	0	2	0	7	0	1	0	7	0	1	0	7	0	1	0
		10	7	0	1	0	6	1	1	0	8	0	0	0	8	0	0	0	6	1	1	0	8	0	0	0
		14	8	0	0	0	8	0	0	0	7	1	0	0	8	0	0	0	6	0	2	0	8	0	0	0
		18	8	0	0	0	8	0	0	0	8	0	0	0												
	Postflight		R + 5 ‡				R + 11																			
		1	8	0	0	0	5	1	2	0																
		4	5	1	2	0	8	0	0	0																
		8	7	1	0	0	7	0	1	0																
		10	8	0	0	0	7	0	0	0																
		14	8	0	0	0	8	0	0	0																
		18																								
Skylab 4 Scientist Pilot	Preflight		L-219				L-130				L-67				L-20											
		1	2	1	3	2	6	1	1	0																
		4	3	1	0	4	5	0	1	2	7	0	1	0	7	1	0	0								
		8	5	0	1	2	6	1	1	0	7	0	0	1	7	0	1	0								
		10	7	1	0	0	8	0	0	0	8	0	0	0	8	0	0	0								
		14									8	0	0	0	7	0	1	0								
		18	6	1	1	0	8	0	0	0					8	0	0	0								
	In-Flight		MD 8				MD 12				MD 26				MD 47				MD 62				MD 81			
		1									7	1	1	1	2	3	3	0	3	2	3	0	1	4	3	0
		4	5	2	2	1	8	0	0	0	5	2	1	0	5	1	2	0	5	1	1	1	4	1	3	0
		8	7	0	1	0	8	0	0	0	7	0	1	0	5	1	2	0	6	0	2	0	4	2	2	0
		10	4	1	2	1	7	0	0	1	4	2	2	0	5	0	1	2	8	0	0	0	5	2	1	0
		14	8	0	0	0	8	1	1	0	8	0	0	0	8	0	0	0	7	0	1	0	8	0	0	0
		18	8	0	0	0	8	0	0	0																
	Postflight		R + 5				R + 11																			
		1	8	0	0	0	5	1	2	0																
		4	5	1	2	0	8	0	0	0																
		8	7	1	0	0	7	0	1	0																
		10	8	0	0	0	7	0	0	0																
		14	8	0	0	0	8	0	0	0																
		18																								
Skylab 4 Pilot	Preflight		L-219				L-130				L-67				L-20											
		1	2	0	2	4	3	2	3	0																
		4	5	1	1	1	4	0	0	4	5	2	1	0	6	0	1	1								
		8	7	0	0	1	4	2	0	2	7	0	0	1	7	1	0	0								
		10	7	0	0	1	6	0	0	2	4	1	0	3	7	0	0	1								
		14	7	0	0	1					8	0	0	0	8	0	0	0								
		18					7	0	0	1	5	1	0	2	8	0	0	0								
	In-Flight		MD 8				MD 12				MD 28				MD 49				MD 62				MD 81			
		1									2	3	1	2	5	1	2	0								
		4	4	1	1	4	7	1	0	0	1	0	1	6	4	1	3	0	6	1	1	0	8	0	0	0
		8	6	1	1	0	5	0	0	3	3	1	0	4	6	1	1	0	3	3	2	0	6	0	2	0
		10	7	0	1	0	3	0	1	6	2	0	0	6	4	3	1	0	4	0	0	4	8	0	0	0
		14	6	0	0	2	7	0	0	1	4	2	0	2	6	1	0	1	4	0	0	2	1	1	0	6
		18	5	0	0	3	8	0	0	0									7	0	0	1	1	0	1	5
	Postflight		R +5				R +11				R + 17															
		1									6	1	1	0												
		4	3	2	3	0	7	1	0	0	3	3	2	0												
		8	7	0	0	1	6	2	0	0	7	1	0	0												
		10	3	0	0	5	7	1	0	0	6	1	0	1												
		14	5	1	0	2	6	1	0	1	6	1	0	1												
		18	2	0	0	6	7	0	0	0																

* Launch minus "n" number of days
† Mission Day "n"
‡ Recovery plus "n" number of days

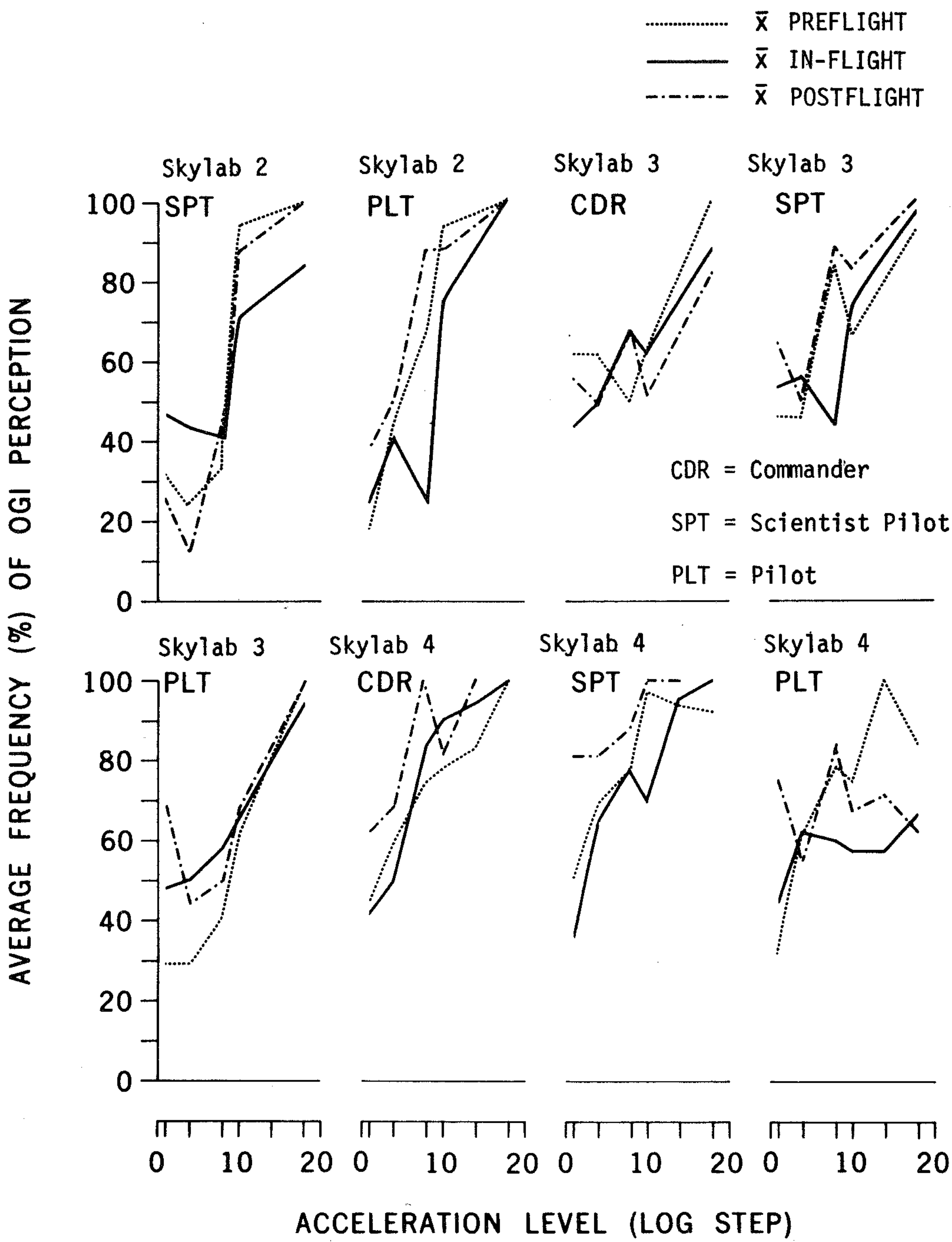

Figure II-3. A summary of the data in table II-I shown as "frequency of seeing" curves with percentage of correct responses among eight trials for each test.

vestibular test goggle on." It was interested to note that prior to unusual performance of the SL 4 PLT on mission day 81, ground-control provided feedback information and question his poor performance (sic)."

In the first mission the Scientist Pilot and Pilot demonstrated higher thresholds under weightless conditions than on the ground; moreover, they showed a greater intersessional range in this response to angular acceleration compared to their preflight and postflight thresholds of response which were similar. These subjects' data reflect their subjective comments that the illusion was in general more difficult for them to perceive in-flight and in particular in the midrange of the acceleration steps. Both subjects reported that at steps 4 through 10 the target often spontaneously appeared to oscillate principally rightward and leftward at a frequency of 1 to 2 seconds. These oscillations were regularly perceived by the Scientist Pilot and sometimes perceived by the Pilot. It is important to note that these oscillations were never observed during ground-based testing preflight or postflight.

In the third mission, the Commander (tested only twice aloft) and Pilot revealed average responses that were similar to their preflight and postflight levels. The Scientist Pilot's performance aloft was slightly but not significantly below that on the ground. All three subjects reported some oscillatory movement aloft but were more aware of drowsiness during the test aloft than on the ground.

The Skylab 4 Scientist Pilot and Pilot of the third and longest mission showed a tendency to perceive the illusion less frequently as the mission progressed, whereas the Commander revealed no consistent change during or after the mission. The Scientist Pilot demonstrated recovery to baseline levels in the first and second postflight trials, 5 and 11 days after recovery, respectively. The Pilot revealed a reversal in his performance on mission day 81, *i.e.*, his performance for the most part declined as the stimulus increased. This unusual response mode persisted in the first test postflight (five days after recovery) but six days thereafter his performance equalled or excelled his preflight scores.

DISCUSSION

The results show that none of the subjects aloft consistently improved in their ability to perceive the oculogyral illusion, whereas four revealed some decrement and the remaining four no consistent change in this perceptual task. In this discussion we will consider possible reasons for the performance decrements including decreases in canalicular sensitivity.

The potential nonvestibular influential factors that were reported by the crewmembers in the first two missions were a spontaneous oscillatory illusion and the soporific effect of the test conditions. During the first mission, the target line of the vestibular test goggle when viewed under certain conditions began to oscillate spontaneously, principally in the horizontal but sometimes in the vertical direction. Movement occurred mainly when the subject was accelerated at midrange levels (table II-I). The Skylab 2 Scientist Pilot, for example, reported: "Remember the left-right, 1-second to 2-second cycling - it was not present in step 1. I noticed it in step 4 and in most of the responses through step 10; and in step 18 I didn't notice it * * *. For me, it was always of equal amplitude and approximately equal frequency. It was really only noticeable at the lower levels of OGI, although I don't remember seeing it at level 1. You might consider something in the way of an optical fatigue or a progressive illusion. Also, it wasn't noticeable at higher levels 10 and 18 when you were seeing a genuine OGI."

The Skylab 2 Pilot observed, "I think predominantly, when I saw this illusion, it was at level 4. I think the frequency was essentially unvarying. However, I had the impression at times and I surmise it's strictly an impression, that instead of oscillating either side of the datum, it would go all to one side, to the left, to my left". Although both astronauts felt that this oscillatory illusion did not interfere with their perception of the oculogyral illusion, the data would indicate otherwise. This space flight illusion of movement cannot be explained by any physical movement of the subject or apparatus. Even when the astronauts attempted to produce this illusion in space by active head movement, they were unsuccessful as reported by the Skylab 2 Pilot in a conversation with mission control: "And the test you wanted us to run, yes, you can excite a movement of the line by gradually very gently rocking your face back and forth. However, that's not what's causing it. I feel very confident because it just looks different. I did not experience the back and forth, left-right oscillations today at any level except 4 and I got it on - I'd estimate a little more than half of step 4." It is interesting to note that the Skylab 2 Scientist Pilot also reported a type of oscillatory movement of the reticle during observations through the onboard telescope. Although acceleration at the step 18 level tended to increase target stability, the registration of this relatively high stimulus level as well as the lesser levels was not as marked in-flight. The Skylab 2 Scientist Pilot describes his change in oculogyral illusion perception as: "Even in step 18 I felt that the OGI responses were not marked, that they were being reinforced by seat of the pants which is pretty definite in step 18, and my general feeling is that the OGI response is not as clean cut as it is on the ground".

The genesis of the oscillatory movement may be related to the drowsiness that was experienced by the astronauts; pendular-type eye movements may be a prominent feature of drowsiness just short of falling asleep. The exclusion of useful visual cues and normal otolithic and other gravireceptor inputs, the restriction of active head or bodily movements, the relatively constant auditory inputs and the gentle rotational movements of the chair evidently constituted a high effective inducement to sleep and its attendant eye movements.

The level of inducement, furthermore, seemed dependent upon the adequacy in terms of quality as well as quantity of an individual's sleep in space. The first mission crew maintained that their sleep was quite adequate; however, the Scientist Pilot who perceived the oscillatory movement of the target more frequently than the Pilot commented, "going through the OGI test, it was very hard to stay awake. If you make your body motionless you just really power down." During the second mission, drowsiness became a more prevalent factor with only the occasional appearance of the oscillatory type of spontaneous illusory movement as reported by the Scientist Pilot and Pilot who were tested six times in-flight (the Commander was tested only twice during the final 15 days of the mission) and showed no appreciable changes. Drowsiness often led to sleep for brief periods. The reduction in scores of the Scientist Pilot and Pilot at times could be attributed to nonperformance due to sleepiness. For example, the Scientist Pilot observed that, "The PLT noted this time and I noted on my run a couple days ago that you get awful sleepy underneath that set of goggles and you really tend to doze off. The PLT had to give a "no" response to a couple of questions simply because he had forgotten that a response was due. He didn't know that I had tapped him. I remember having done the same thing on my run." The Pilot suggested: "It would be a good idea to schedule OGI in the morning because it's awful easy to go to sleep with that experiment, difficult to concentrate especially in the afternoon. You could even go to sleep real easy in the morning. It's a good sleep-inducing experiment, and it should be done when you're fresh." His suggestion was followed and after mission day 32 testing was carried out in the morning rather than the afternoon but no real changes were noted. It is significant that drowsiness was never experienced by any of the subjects during either preflight or postflight testing. Curiously, although the Skylab 3 Scientist Pilot aloft noticed a greater sensitivity to rotation at step 18, his general ability to perceive the illusion was less.

The results obtained in the Skylab 4 mission are at once the most important (because of the duration) and most difficult to explain.

The Commander's performance was much the same aloft as on the ground, but the Scientist Pilot's performance aloft was lower than on the ground. For as yet unexplained reasons, the Pilot showed a curious reversal in slope of his resultant curve on the last mission test day and the first test postflight. In the second test postflight his perception of the oculogyral illusion was excellent, comparable to his best performance preflight and far exceeding his scores made after mission day 12.

TENTATIVE CONCLUSIONS

° The fact that the performance of all of the Skylab 3 crewmen and the Skylab 4 Commander was about the same aloft as on the ground demonstrated that they experienced no inhibitory influences reducing the effective "sensitivity" of the semicircular canals. In consequence, the small decrements in performance manifested by the remaining four participants cannot be regarded as "the rule".

° The differences in performance between the two groups might be explained on the basis of less favorable testing conditions aloft or simply represent individual differences.

° In any event, the behavior of the oculogyral illusion in weightlessness is different from that reported for nystagmus measured during parabolic flight. This is of theoretical interest, at least, contributing to the evidence that these two responses have different underlying mechanisms.

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III. THE PERCEIVED DIRECTION OF INTERNAL AND EXTERNAL SPACE

ABSTRACT

Two series of tests were conducted. In each series the rotating litter chair was used in different positions:

° upright or tilted slightly in pitch and roll, and

° horizontal or tilted slightly in pitch and roll.

In one series a modification of the vestibular test goggle was used that enabled the subject to indicate the position of a line-target system within the roll and pitch planes. In the other series a rod-and-sphere device was used that enabled the subject with eyes covered to indicate the perceived direction of space without furnishing adequate cues. All of the tests were carried out in the workshop whether aloft or on the ground. In all test situations the subject's task was to use the workshop as the frame of reference and indicate either his internal body axes or the vertical and horizontal of the workshop, the external frame of reference. The analysis of the findings is incomplete, but the plots show that the results using the vestibular test goggle was similar aloft and on the ground. The results using the rod-and-sphere device were quite different in the two environments; the estimates were fairly accurate on the ground and the "deviations" aloft exhibited characteristic patterns.

INTRODUCTION

In Gemini flights V and VII an experiment was conducted in which the astronaut's task was to set a dim line of light (in an otherwise dark field) to an external horizontal reference. Aloft this reference was a panel horizontal with reference to the astronaut's seat while on the ground the test was conducted with the astronaut secured in the gravitational upright position. Except for a systematic error in the case of one astronaut the settings made aloft were as accurate as on the ground. The inference drawn was that relatively meager touch, pressure and kinesthetic receptor cues served as well as the more plentiful nonvestibular and otolithic cues on the ground. It was these findings that generated the interest to repeat the experiment under far more favorable conditions in Skylab missions (1).

<u>Astronauts</u>

In the Skylab 2 mission it was decided that the Commander would not participate in the oculogyral illusion or motion sickness susceptibility tests. It was left to the Commander to determine whether and to what extent he would act as a subject in the space perception tests.

Apparatus

Goggle Device. Devices for studying the visually perceived direction of space in the absence of visual cues have long been in use, but the principle underlying such devices is so simple that its elegance is seldom appreciated. The basic device is a visual target, usually a line pattern of light on a dark background, that can be manipulated to indicate the direction of space yet afford no clue to its direction.

The so-called vestibular test goggle used in the Gemini V and VII experiment was modified for the specific purpose of the Skylab mission.

The overall appearance of the goggle is shown in figure III-1. The inner surface of the goggle forms the soft-cushion carrier portion structured so that it may be pressed firmly against the subject's face without discomfort. The mask section of the goggle forms the rigid base for

- attachment of the target and optical system,
- gear mechanisms and scales for adjustment and reading out the positions of the target in the roll and pitch planes,
- stabilization of the coupling to the biteboard assembly, and
- the external cover.

The slit target consists of a single 0.1 mm x 0.55 mm sealed vial of tritium gas (U.S. Radium Corporation - Atomic Energy Commission license 09-06979-03) which requires licensing for handling. The self-luminous light source has a relatively constant level of illumination over a half-life of 12 years without bulbs, batteries, and wiring which would require periodic servicing and replacement. High reliability and essentially complete safety of this light source are assured by a rugged housing qualified to withstand spacecraft launch forces. The target light is collimated by a triplet located near the subject's eye. The position of this triplet can be adjusted toward or away from the target with a fine threaded screw adjustment to correct for a wide range of spherical refractive errors of the subject, thereby ensuring a sharp image of the test target for each subject.

The pitch of the target is adjusted (throughout a range of ±20 degrees relative to a reference plane normally at eye level when the subject is upright) by means of a knurled knob (fig. III-1) that activates a mechanical link to a rack and pinion gear. The target's roll position can be changed by rotating a second knurled knob (fig. III-1) linked to a helical gear arrangement (36:1 ratio); fine rotary adjustment

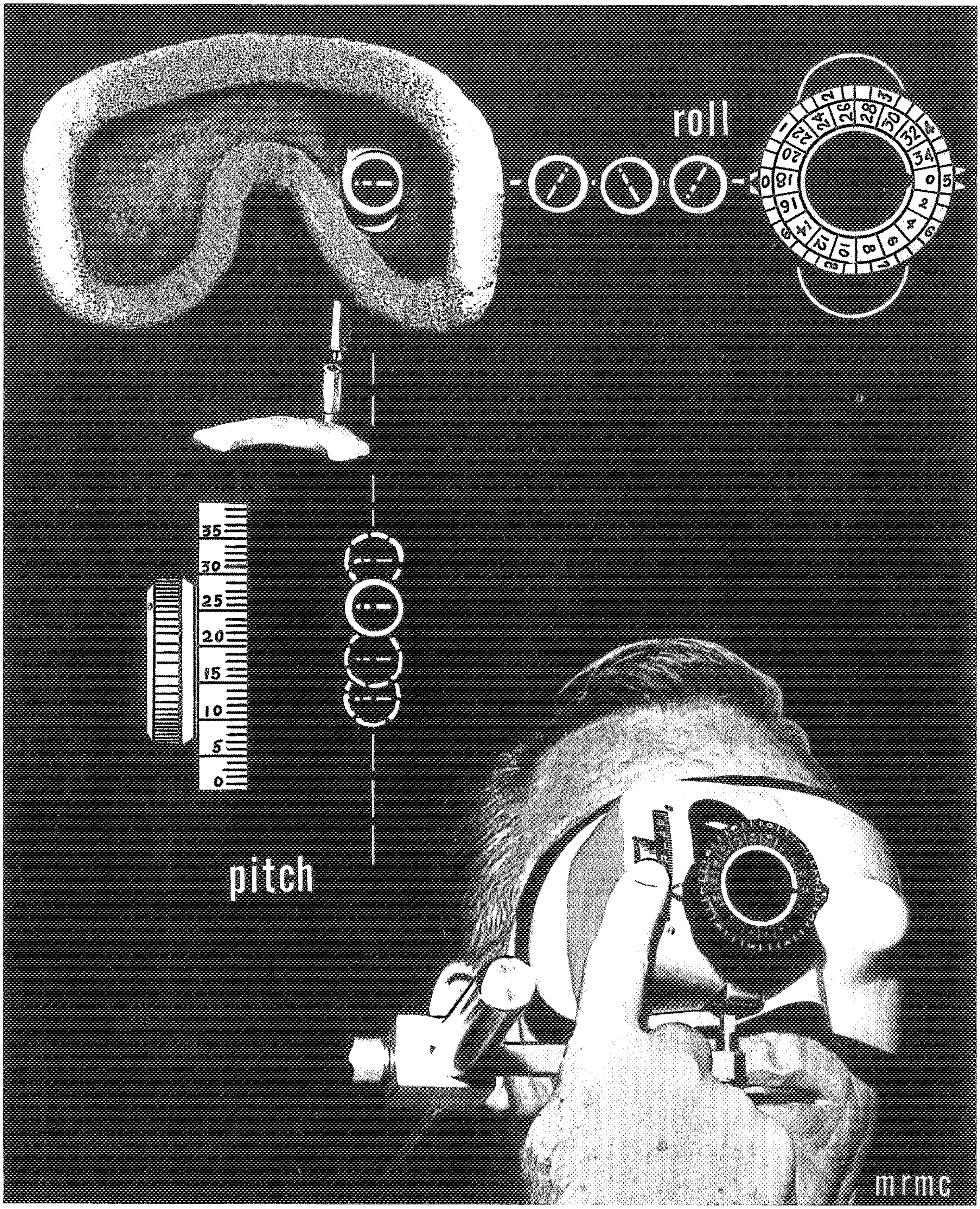

Figure III-1. Goggle device showing behavior of the target in the pitch and roll planes.

can be made without limit in the clockwise or counterclockwise direction. The line pattern target was designed with a break at its center, serving as a visual reference point and a break near one of its ends to indicate polarity. The entire target and optical system is arbitrarily placed in the right half of the goggle for viewing by the right eye only.

The device weighs less than one pound and is easily supported and held firmly against the subject's face solely by his teeth interfacing with the biteboard assembly. Dental impression material softened by heat or more permanent material fashioned by a molding process is deposited on the biteboard for custom fitting. One model of the goggle is provided with scales for direct readouts, another with potentiometers for continuous writeouts.

Rod-and-Sphere Device. Most devices for indicating the upright are confined to movement in one plane. The rod-and-sphere device shown in figure III-2 was fabricated specifically for the Skylab experiment. The reference sphere is a 6-inch diameter, lightweight (12 ounces), hollow, metallic sphere that is used in conjunction with the magnetic pointer. The pointer is attached to the rotating litter chair by means of a flexible arm that contains readouts for indicating the pointer's pitch and roll position with reference to the sphere, but not translational movements. This arrangement allows considerable freedom of movement of the device without reference cues to the rotating litter chair.

In using the rod-and-sphere device it is not possible to set the rod, say, to the upright in the frontal plane first, then make the setting in the saggital plane. Instead, the final setting must be reached incrementally, *i.e.*, usually two or three steps. The astronauts did not regard this constraint a significant handicap.

On the ground the weak magnetic field made it necessary for the subject to exert pressure to keep the rod on the sphere unless the rod was near the gravitational upright; the rod-and-sphere device was easier to use in weightlessness than on the ground.

Chair Device. The rotating litter chair could be perfectly positioned with regard to the visual upright of the workshop. When tilted forward 11.01° from the upright there was an inescapable leftward roll of 4.5°. In the litter mode when the rotating litter chair was horizontal there was a roll of 0.9° leftward; when tilted head upward 12.1° the leftward roll was 4.95°.

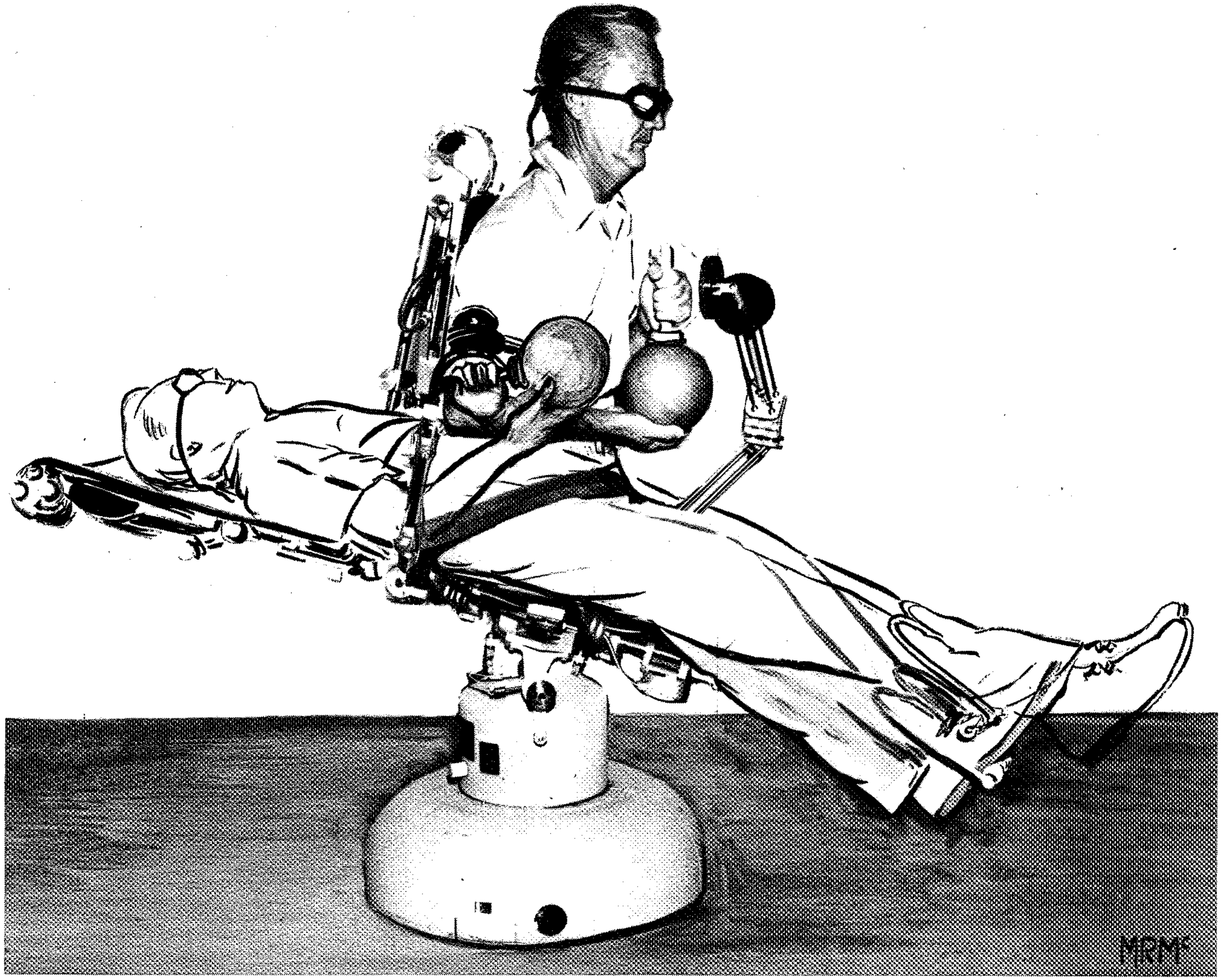

Figure III-2. Rod-and-sphere device with subject manipulating the rod in two typical positions.

Water Immersion Tank. A small facility was constructed to carry out the space perception tests underwater. The object was to simulate weightless conditions with regard to touch, pressure and kinesthetic receptor systems but preserve otolith function.

Plan

In using the goggle device the subject grasps the bite piece with his teeth, which causes his face to come in firm contact (in a repeatable fixed position) with the goggle surface. He then closes his eyes for 60 seconds, opens his eyes, and sets the target in the roll and pitch planes to internal references (the target aligned with his longitudinal body axis and its broken tip pointed toward his head and its center in the "straight-ahead" position). The subject closes his eyes and signals the observer when he has completed this task. The observer then reads and records (in the onboard log book) the settings, after which he offsets the target in some random fashion. This procedure is repeated for a total of five times. The subject next relaxes his bite and moves backward from the goggle to observe his position relative to the Skylab for a 10-second period. He then reassumes the test position and sets the target in relationship to the external reference (target aligned with the longitudinal axis of the Skylab and its broken tip pointing "upward," and its center at eye level with reference to the Skylab floor). The subject then closes his eyes and signals the observer to record and offset the target. This cycle is repeated until five pitch and roll settings have been recorded. This entire procedure of internal and external spatial localization is repeated with the chair in its tilt positions.

The chair is returned to upright, and the observer next attaches the magnetic pointer and readout device to the chair. The vestibular test goggle is removed, and the subject's eyes are covered with the blindfold. The subject grasps the sphere in his left hand, the magnetic pointer in his right, and attempts to align the pointer in a manner analogous to the visual judgments. For the internal reference judgments, the pointer is placed parallel to the apparent long axis of his body with its free end pointing in the direction of his head; for the external judgments, the pointer is aligned with the perceived direction of the Skylab longitudinal axis and pointed upward. Five internal and external reference settings (each separated by the subject releasing the rod and the observer offsetting it) are obtained both in the upright and tilted chair positions. The rotating litter chair is finally converted to its litter mode and the same procedure for measuring the nonvisual perception of space with the rod/sphere device is conducted with the litter horizontal as well as tilted.

RESULTS

All of the findings (none for water immersion) have been plotted in terms of the astronaut's actual settings. In general, the settings using the goggle show a strong tendency to cluster, the settings made on the ground overlapping those aloft. Occasionally there is a systematic deviation from the "perfect" score. The plots not only are difficult to envision in terms of the position of the subject but also in terms of the measurements of the errors. In consequence, the data is being replotted in terms of actual positions the subject indicates with reference to the workshop, and small line drawings will allow the reader immediately to grasp the stimulus situation.

The plots using the rod-and-sphere device show considerable scatter except when the chair is upright in the ground-based workshop. Settings made aloft show a tendency toward deviations of a similar nature.

ACKNOWLEDGMENTS

We grasp this first opportunity to name the men who not only acted as subjects and observers but whose quick minds contributed much information greatly extending the value of data points: Skylab 2: Charles Conrad, Joseph P. Kerwin and Paul J. Weitz; Skylab 3: Alan L. Bean, Owen K. Garriott and Jack R. Lousma; Skylab 4: Gerald P. Carr, Edward G. Gibson and William R. Pogue.

In organizations NASA-sized quick response to change in conditions is "against the rule", yet management (notably Mr. Richard S. Johnston and Dr. Lawrence F. Dietlein) recommended what amounted to doubling the number of subjects in studying the susceptibility to motion sickness.

None of the equipment in the workshop failed; even a loss of pressure in the nitrogen blanket around the rotating litter chair motor, for example, would have cancelled the tests described in the first two parts of this report. For elegance in workmanship in fabricating the chair and other equipment, we wish to acknowledge the professional skill and judgment of Charles M. Blackburn and his associates at the Johns Hopkins Applied Physics Laboratory.

Our indebtedness also extends to many other persons of good will at the Johnson Space Center and elsewhere, many of whom cannot be named. We do wish to mention, however, the critical roles played by Drs. Charles E. Ross and Paul Buchanan; the engineers in the Project Engineering Branch, Mr. James S. Evans and Mr. William J. Huffstetler; and our chief assistant, Mr. Charles H. Diamond, Jr.

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THE EFFECTS OF PROLONGED EXPOSURE TO WEIGHTLESSNESS ON POSTURAL EQUILIBRIUM

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ABSTRACT

Postural equilibrium performance by the Skylab 2, 3, and 4 crewmen following exposure to weightlessness for 28, 59 and 84 days, respectively, was evaluated using a modified version of a quantitative ataxia test developed by Graybiel and Fregley. The test employed a series of narrow metal rails of varying widths on which the crewman was required to maintain an upright posture with his feet tandemly aligned and arms folded across his chest. Performance for this test was measured under two sets of conditions. In the first the crewman was required to maintain postural equilibrium on the rail (or floor) with his eyes open. In the second condition he attempted to balance with his eyes closed. In both cases performance was scored in terms of time (in seconds) on the rail before losing balance. Preflight baseline data were obtained on three separate occasions for each of the crewmen. Tests following the 28-day, Skylab 2 mission were limited to balancing with eyes open and eyes closed while standing on the floor only. Postflight data were obtained at 1, 9, and 29 days following mission termination for the Skylab 3 crew and at 1, 4, 11, and 31 days following mission termination for the Skylab 4 crew.

A comparison of the preflight and postflight data indicated moderate postflight decrements in postural equilibrium in three of the crewmen during the eyes open test condition. However, in the eyes closed condition, a considerable decrease in ability to maintain balance on the rails was observed postflight for all crewmen tested. The magnitude of the change was most pronounced during the first postflight test day. Improvement was slow. However, on the basis of data obtained, recovery to preflight baseline levels of performance was evidently complete at the end of approximately two weeks for all crewmen. The findings are explained in terms of functional alterations in the kinesthetic, touch, vestibular, and neuromuscular sensory mechanisms induced by the prolonged absence of a normal gravitational stimulus.

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INTRODUCTION

In his normal gravitational environment man has four sources of sensory information which can be used to maintain postural equilibrium: vision, vestibular inputs, kinesthesia, and touch. Of these senses the superiority of vision as a basis of postural stability has been demonstrated by a number of investigators (1, 2, 3, 4, 5, 6, 7, 8). Even when other systems are nonoperative, vision can be employed to maintain upright posture. On the other hand, provided that the mechanoreceptors are intact, vision is not essential as evidenced by the observation that blind people have little difficulty in maintaining postural equilibrium (3).

There is also little doubt that functional disturbances in the vestibular, kinesthetic, and tactile sensory modalities can affect postural stability. People who have experienced unilateral labyrinthine or cerebellar damage will often fall to the side of the lesion (9). Patients with bilateral labyrinthine disturbances, on the other hand, frequently appear to exhibit little disability in maintaining a steady posture when standing with feet together and eyes closed in the Romberg position (10). When the testing procedure is improved, however, and a sharpened Romberg is employed (11), bilateral labyrinthine defects as well as other less dramatic vestibular disturbances do result in postural difficulties that are evident when the eyes are closed (12). These observations suggest that, in a closed loop system, the sensory basis of postural stability must include inputs from kinesthetic, pressure, and touch receptors, as well as visual and vestibular inputs (13, 14).

That exposure to the dramatically altered environment encountered during weightless space flight may affect postural stability has been under investigation by our laboratories beginning with the Apollo 16 mission. Although complete data are not available from Apollo 17, preflight and postflight testing of the Apollo 16 crewmen indicated some decrement in postural equilibrium three days following recovery when the crewmen were tested with their eyes closed (15). Using a measurement procedure referred to as stabilography, investigators in the Soviet Union have reported that the crewmen of the 18-day Soyuz 9 mission manifested difficulty in maintaining a stable vertical posture which did not normalize until ten days after the flight. The greatest disturbances were measured during an eyes closed test condition (16).

On the basis of these observations it was hypothesized that, with prolonged exposure to a weightless environment, those sensory systems, with the possible exception of vision, necessary for the maintenance of postural stability, will undergo some changes. Further, these

changes are most likely originally peripheral, and involve the modification of inputs from the receptors serving kinesthesia, touch, pressure, and otolith function. As exposure is prolonged, habituation responses occur at a central level in the nervous system which constitute learning in a new environment. When the environment is again changed from weightlessness to 1-g reference, ataxia and postural instability will be manifested as the result of the neural reorganization that has occurred in weightlessness.

The specific objective of this investigation was to assess the postural equilibrium of the Skylab astronauts following their return to a 1-g environment and to suggest possible mechanisms involved in any measured changes.

METHOD

Postural equilibrium was tested by a modified and shortened version of a standard laboratory method developed by Graybiel and Fregly (11). Metal rails of four widths, 1.90, 3.17, 4.45, and 5.72 centimeters (0.75, 1.25, 1.75, and 2.25 inches), provided the foot support for the crewman during the preflight and postflight tests. In addition, rail widths of 1.27 and 2.54 centimeters (0.5 and 1.0 inches) were available for preflight testing only. A tape approximately 10.16 centimeters (4.0 inches) wide and 68.5 centimeters (27.0 inches) long served as a foot-guide alignment when the crewman was required to stand on the floor. Each crewman was fitted with military-type shoes for this test, both preflight and postflight to rule out differences in footwear as a variable in intrasubject and intersubject comparisons.

The test rails and required body posture are illustrated in figure 1. Time, which was the performance measure of balance, began when the crewman, while standing on the prescribed support with his feet in a tandem heel-to-toe arrangement, folded his arms. His eyes remained open in the first test series. In the second series the time measurement was initiated after the crewman attained a balanced position and closed his eyes. During initial preflight testing several practice trials were allowed on representative rails until the crewman demonstrated full knowledge of the test procedure and reasonable confidence in his approach to this balancing task.

During a test session the initial rail width for testing with eyes open was typically 3.17 centimeters (1.25 inches). Three test trials with a maximum required duration of 50 seconds each were given. If the time limit was reached in the first two trials, a third was not performed, and a perfect score of 100 seconds was recorded for the initial support width. If the crewman failed to obtain a perfect

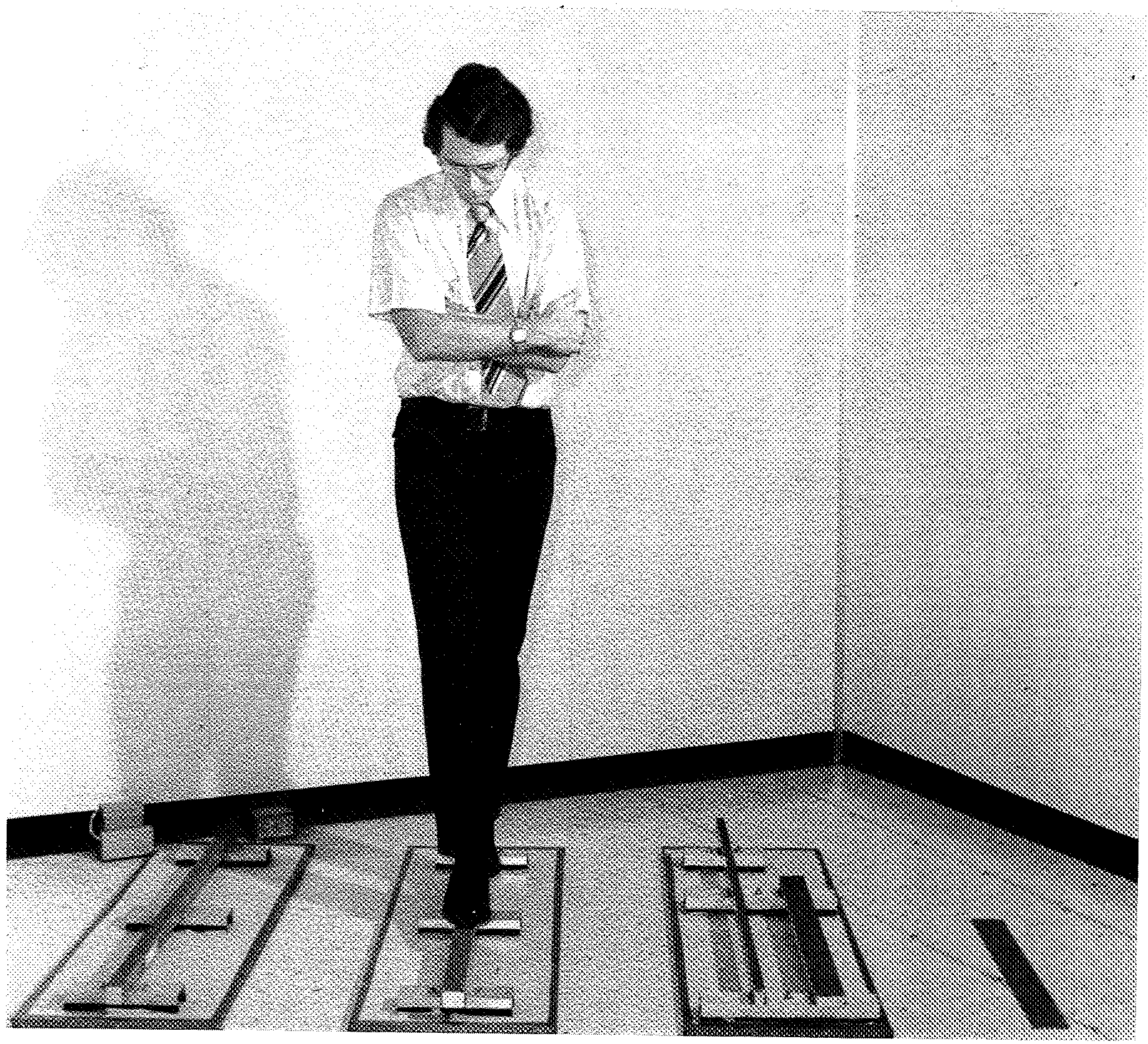

Figure 1. Illustration of postural equilibrium test rails and a subject demonstrating the required test posture.

score, the two largest time values for the three trials were summed to obtain the final score. The choice of the second rail width depended upon the crewman's performance on the initial support width. If his score was greater than or equal to 80 seconds, the next smaller support width was used; if his score was less than 80 seconds, the next larger support width was used. Testing on a third rail size was required when both of the two previous support width scores fell either above or below the 80-second performance level. Testing with eyes closed followed the same procedure except that a larger rail support, 5.72 centimeters (2.25 inches) was typically used initially. Eyes closed testing always followed testing with eyes open. The time required to perform the entire test was approximately 18 minutes. All tests were conducted with normal laboratory illumination.

Three preflight baseline tests were performed on each of the Skylab 2, 3, and 4 crewmen approximately six months prior to their space flights. These postural equilibrium tests were part of a comprehensive battery of vestibular tests completed by each of the crewmen at the Naval Aerospace Medical Research Laboratory.

Tests following the 28-day Skylab 2 mission were limited to balancing with eyes open and eyes closed while standing on the floor only. These tests were conducted during the first and second day following splashdown. Postflight tests on the Skylab 3 Scientist Pilot and Pilot were conducted on the second, ninth and twenty-ninth day following termination of their 59-day mission. The Skylab 3 Commander was excluded from postflight testing because of an acute back muscle strain acquired on the first day postflight which might have been aggravated by the test procedure and which, in any event, would have affected his performance on the rails. Postflight tests on each of the Skylab 4 crewmen were conducted on the second, the fourth, the eleventh and the thirty-first day postflight. The Skylab 4 flight was 84 days in duration. With both of the latter two crews the tests on the second day following splashdown were conducted onboard the recovery ship which was tied to a dock and, therefore, provided a stable platform. All subsequent postflight tests were conducted at the Johnson Space Center.

RESULTS

Postural Equilibrium Tests

Preflight data obtained on these crewmen indicated that they were all well within the range of postural equilibrium performance typically exhibited by young, healthy aviator-type subjects.

The limited postflight data collected on the Skylab 2 crewmen indicated that they all experienced considerable difficulty with standing on the floor during the eyes closed test condition. They had no trouble, however, in meeting the performance criterion when permitted the use of visual cues. In considering the significance of these data, it must be remembered that the tests were performed on a moving ship.

Data obtained preflight and postflight on the Skylab 3 Scientist Pilot and Pilot and the Skylab 4 Commander, Scientist Pilot, and Pilot are presented in figures 2 to 6, respectively. In these figures eyes open and eyes closed postural equilibrium performance on each of the rail sizes used, plus the floor, is plotted as a function of test day. The baseline data point shown against which the postflight data are compared is the mean of the preflight data for that condition. The standard error of the mean was selected as a descriptor of the variance observed in the baseline data and is represented by dashed lines. Approximately 50 percent of those cases where no variance is indicated are the result of having only a single data point on the rail size in question; otherwise, the standard error of the mean is less than one.

Visual inspection of figures 2 and 3 indicates that the Skylab 3 Scientist Pilot and Pilot showed a decrease of approximately the same magnitude in eyes open postural equilibrium performance when tested on the second day after splashdown. However, a more pronounced decrement in ability to maintain an upright posture was observed in the eyes closed test condition. This change was more evident in the Pilot and is clearly demonstrated by the 5.72 centimeter (2.25 inches) rail size data seen in figure 3. Indeed, without the aid of vision on the second day of recovery, the Pilot experienced considerable difficulty even when attempting to stand on the floor, a condition he was never confronted with preflight because of his excellent balance on the 4.45 centimeter (1.75 inches) and 5.72 centimeter (2.25 inches) rail sizes. Complete recovery to preflight levels of performance did occur in both the eyes open and eyes closed conditions for both of these crewmen. However, the rate of recovery for the Pilot was apparently slower as evidenced by his relatively poor score on the 5.72 centimeter (2.25 inches) rail on the ninth day after recovery.

In contrast to the Skylab 3 crewmen, the Skylab 4 Commander and Pilot demonstrated no decrease in their postflight eyes open postural equilibrium as measured by this procedure (figures 4 and 5). They did, however, show a very large deficit in ability to balance with eyes closed. In the case of the Commander, this postflight change is clearly indicated on the first day after recovery with the 5.72 centimeter (2.25 inches) wide rail. Also, it can be seen that on the first day after recovery he was almost unable to maintain the required

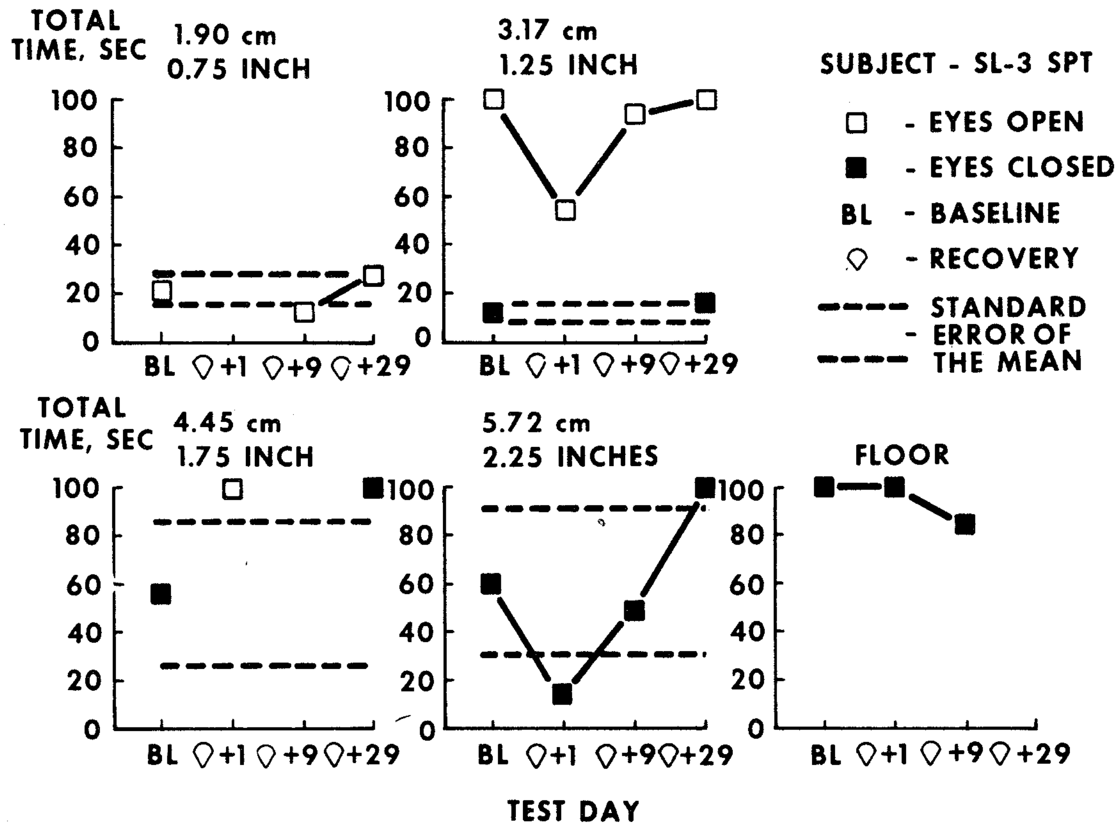

Figure 2. Postural equilibrium test performance for the Skylab 3 Scientist Pilot. The abscissa for each rail size shown indicates the days on which testing occurred, including a mean baseline (BL) value. The ordinates show total time on the rails where total time is the sum of the best two of three trials. Data obtained with eyes open and eyes closed are indicated by closed circles and triangles respectively. The dashed lines represent values for the standard error of the baseline mean.

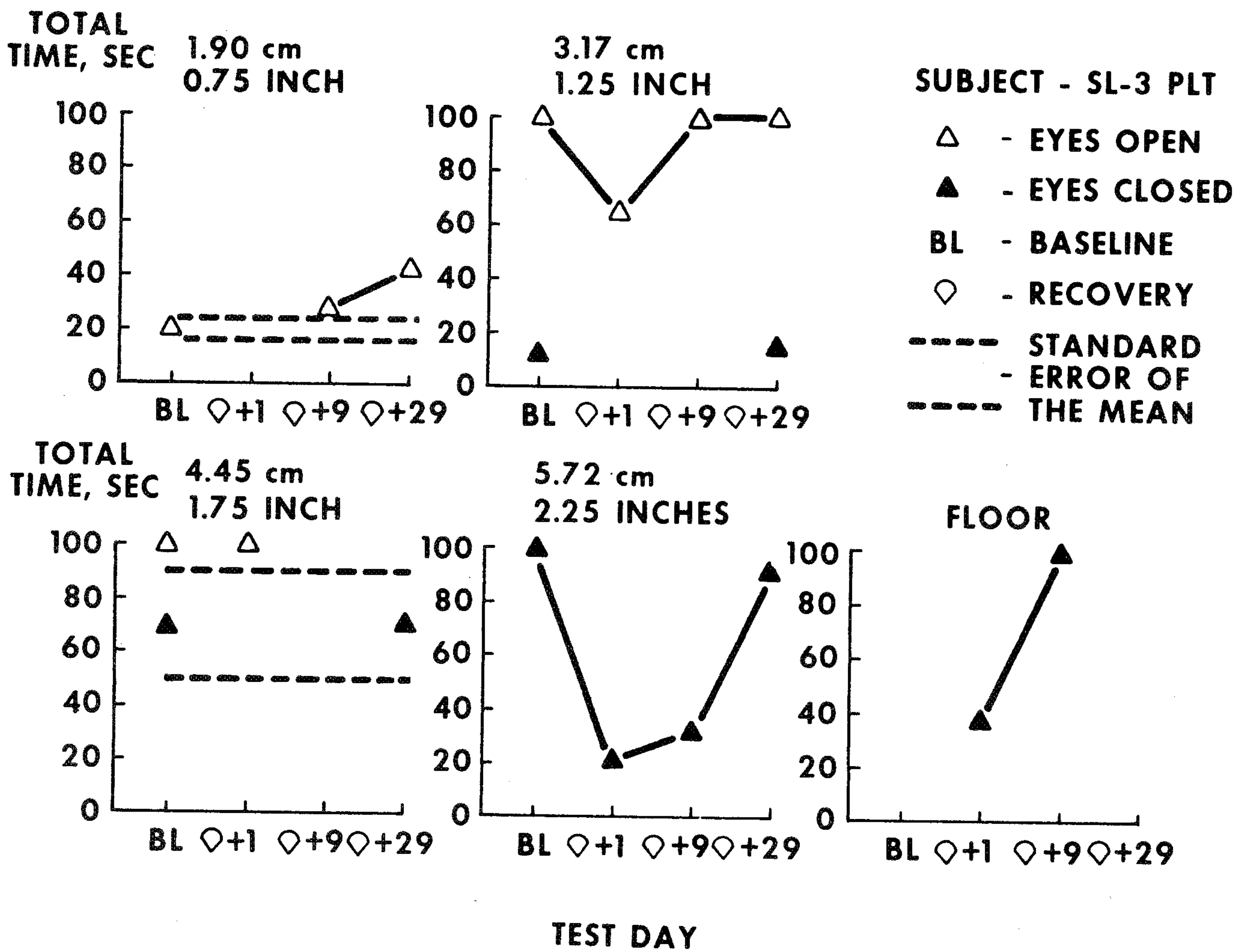

Figure 3. Postural equilibrium test performance for the Skylab 3 Pilot. The parameters are the same as those described for figure 2.

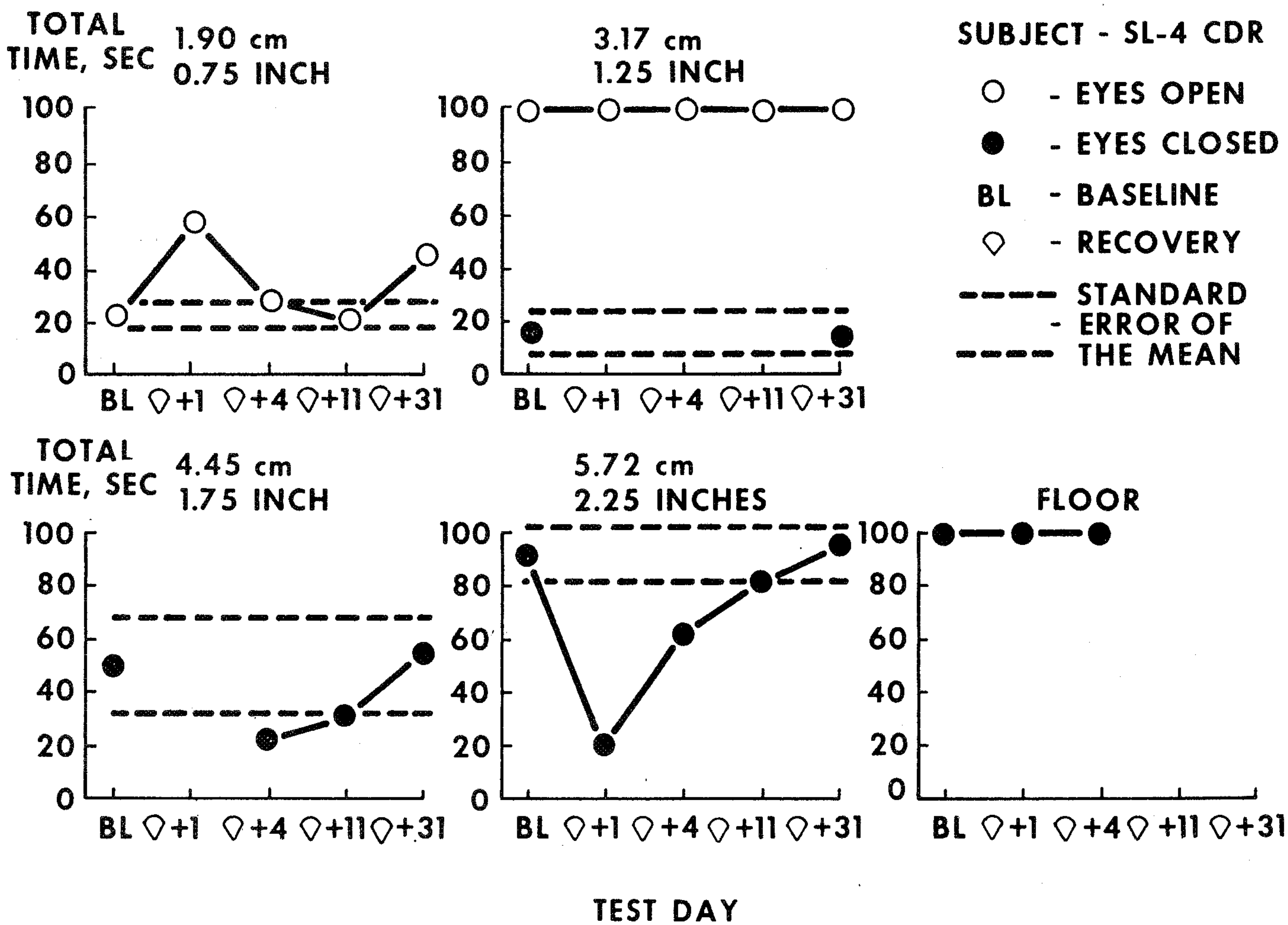

Figure 4. Postural equilibrium test performance for the Skylab 4 Commander. The parameters are the same as those described for figure 2.

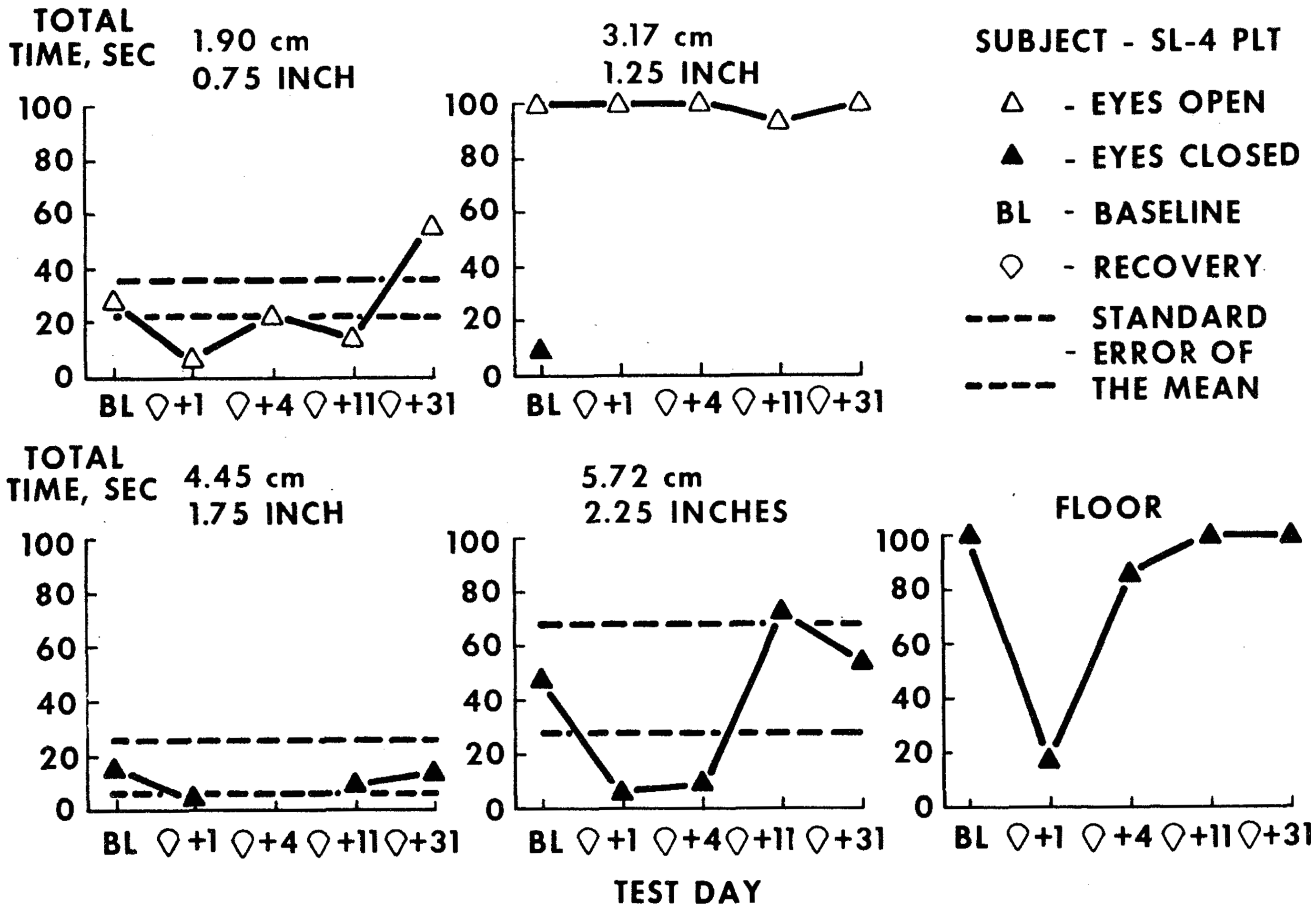

Figure 5. Postural equilibrium test performance for the Skylab 4 Pilot. The parameters are the same as those described for figure 2.

vertical posture while standing on the floor with his eyes closed. Improvement was evident on the fourth day after recovery, and the data obtained on the eleventh day indicates that both of these crewmen had regained their preflight level of ability on the eyes closed portion of this task.

Data obtained on the Skylab 4 Scientist Pilot are presented in figure 6. It can be seen that, like the Skylab 3 crewmen, the Skylab 4 Scientist Pilot experienced a postflight decrease in ability to maintain postural equilibrium in both the eyes open and eyes closed test conditions. The magnitude of change was much greater without vision. On the fourth day after recovery this change was still very evident, but by the eleventh day this crewman's ability to balance on the test rails had returned to baseline proficiency.

Subjective Reports and Observations

The postflight decrease in postural stability demonstrated by the rail tests are supported by observations of and subjective reports by the crewmen.

Although all of the Skylab crewmen were able to walk with minimal or no assistance immediately after exiting the Command Module, they did so with noticeable difficulty. During this initial postflight period on the recovery ship, they tended to use a wide-stanced shuffling gait with the upper torso bent slightly forward. With each passing hour back in the one-g environment, they gained confidence and proficiency in their ability to walk about unaided. By the end of the first recovery day all of the crewmen showed considerably improved ambulatory performance and by the time they were ready to disembark the recovery ship on the second day after recovery, they manifested few noticeable signs of ataxia or postural instability.

During the first several days following splashdown, and especially on the first recovery day, all of the crewmen reported that the simple act of walking required a conscious effort. The Skylab 3 Commander, for example, reported that, when he stepped forward, he had a feeling that he was moving sideways. Also, nearly all of the crewmen reported that they had to be especially careful when walking around corners because they had tendency to fall to the outside. This problem was described by a few of the crewmen as a sensation of forced lateral movement.

Related to these subtle disturbances in postural stability was the report by all of the crewmen that rapid head movements produced a sensation of mild vertigo. This sensation could be effectively controlled by holding the head steady. Several of the crewmen,

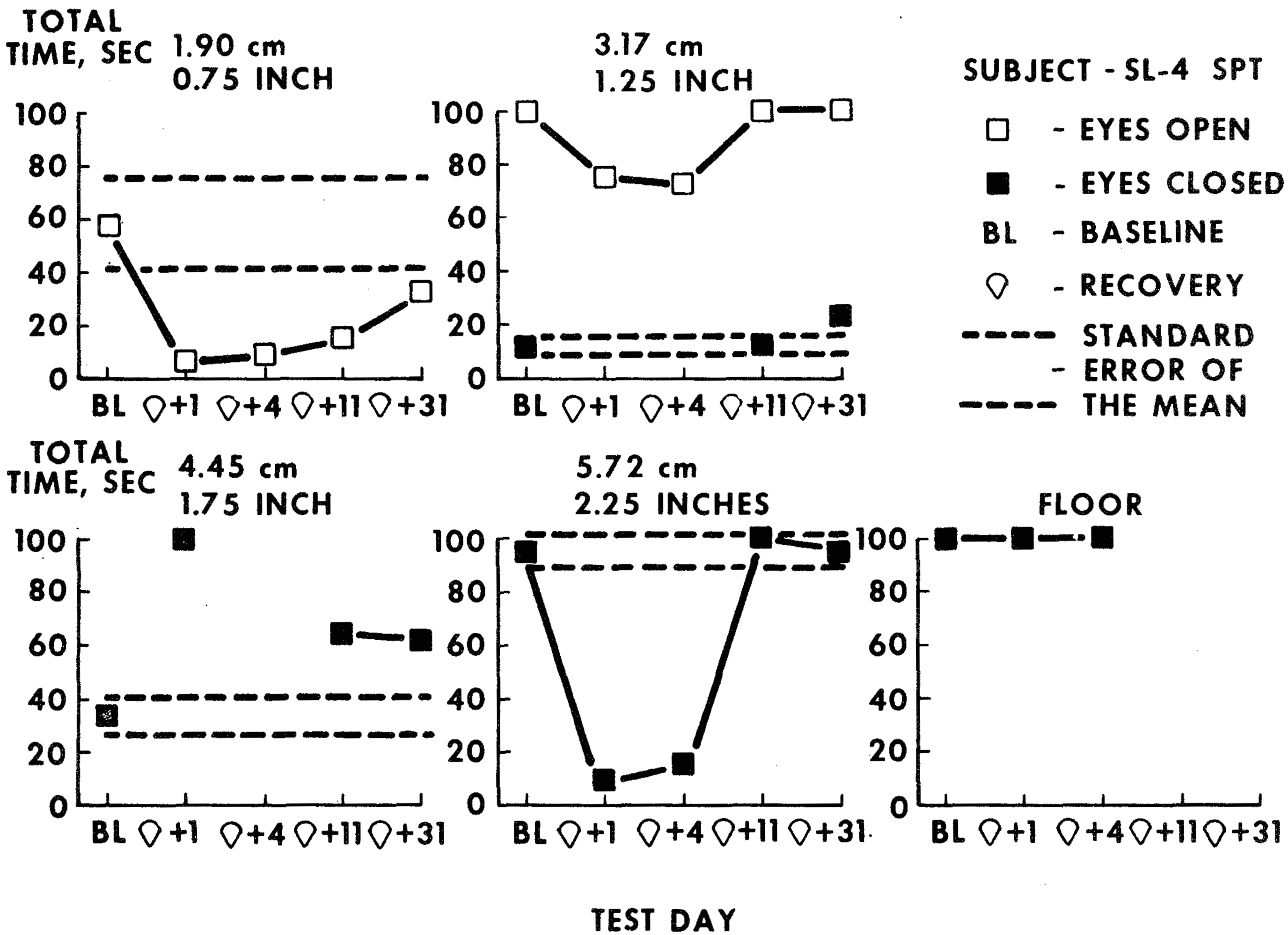

Figure 6. Postural equilibrium test performance scores for the Skylab 4 Scientist Pilot. The parameters are the same as those described for figure 2.

including the Skylab 4 Commander and Pilot, indicated a particular need to hold their head steady while attempting to balance on the test rails. Any slight head movement, especially during the eyes closed test condition, would induce the vertigo sensation and cause them to lose balance. The movement-induced vertigo diminished gradually and in most cases was gone within three to four days following splashdown; however, the Skylab 4 Pilot reported that he occasionally experienced mild vertigo with rapid head turns as late as eleven days after recovery. It is also of interest to note that on the second and fourth days after recovery, the Skylab 4 Pilot reported experiencing a "wide dead-band" when attempting to balance on the test rails with his eyes closed. In other words, he was unable to accurately sense small displacements of his head and body.

Because the postflight test intervals were infrequent and not at the same times for each crew, the time course to complete recovery cannot be clearly specified. However, on the basis of observations and data obtained, it appears that the Skylab crewmen required up to ten days to regain their normal postural stability. These results are in close agreement with the Soyuz-9 postflight postural stability findings reported from the Soviet Union.

DISCUSSION

The results from the present study provide evidence that postural stability can be affected by prolonged periods of exposure to weightlessness. Support for the hypothesis that central neural reorganization occurs in response to environmental change is obtained when the postflight decrease in stability on the rails and the time course for recovery is compared with preflight performance.

That adaptive changes may occur and contribute to disturbances of equilibrium following exposure to a weightless environment is reasonable from a physiological point of view. As one basis of postural stability, vision can expect to undergo little change. However, the vestibular apparatus (particularly otolith input), kinesthesia, and touch will be those sensory systems most affected by exposure to zero-g.

Subgravity levels can be experienced in parabolic flight, free fall, and short jumps. Water immersion and sensory deprivation procedures minimize stimulation of kinesthetic and touch receptor systems without lifting the gravitational load on the otolith receptors. It is only in space flight that prolonged periods of weightlessness can be achieved. During these periods, kinesthetic and touch stimulation is reduced and otolith input is considerably modified. Static otolith

output cannot in this latter situation provide information for spatial orientation (spacecraft vertical) nor can kinesthesia or touch provide reliable sensations unless the crewman is in contact with a rigid surface to provide some reference point.

That these sensory systems can habituate to the weightless environment is suggested by the increased ability with time for the crewmen to maneuver with decreasing difficulty. In this regard physiological evidence has been obtained that suggest adaptation toward the norm in the frog's otolith system following four to five days exposure to weightlessness (17). It is also possible that habituation in weightlessness of the sensory systems basic for postural stability is similar to the changes experienced in other unusual force environments such as prolonged exposure to slowly rotating rooms and movements encountered on ships.

If this is the case, then several mechanisms could be proposed to account for the changes occurring as a result of exposure to weightlessness. First, a central nervous system "pattern center" concept (18) could be postulated to help understand the possible mechanism encountered in the habituation process. For example, following insertion into orbit the crewmen may experience difficulty in maneuvering and find orientation to be a problem. After four to five days, movement from one area of the vehicle to another would become somewhat easier. Fine motor control to determine displacement would be established. Adaptation in the postural mechanicomotor system would have occurred.

On the basis of the postulated pattern center, the radical environmental change encountered in transitioning from one-g to zero-g would result in vastly different outputs from the otolith, kinesthetic, and touch receptors. These altered outputs would then be sent to their corresponding centers and these in turn relayed to the pattern center, where a copy of the appropriate movement was stored progressively over time. Once an adequate memory of the pattern is built up, the pattern center would take over movement and automatic balance control. Further, under control of peripheral inputs from the otolith, kinesthetic, and touch receptors relaying the actual movement, the center would permit anticipation of the coming movement. Return to a one-g environment would result in a recurrence of difficulty, both in locomotion and postural equilibrium. Habituation to a gravity reference would begin almost immediately and a new effective pattern in the pattern center would be established possibly in a time proportional to the previous duration of weightless exposure.

A second mechanism could possibly be responsible for the changes noted in postural stability. Biostereometric analysis of body form indicated that the crewmen experienced a measurable postflight reduction in body tissue volume, part of which was muscle tissue (19). A significant percentage of the total volume loss noted was in the thighs and calves. A postflight decrease in leg strength was also measured (20). In the case of the Skylab 3 crew the average leg strength loss was approximately 20 percent. As the present task required standing on the rails in a sharpened Romberg position, it is possible that the crewmen were physically incapable of completing the task due to disuse atrophy of the major weight bearing muscles.

A third alternative is also possible. Both a hyper Achilles tendon reflex and an increased gastrocnemis muscle potential were observed postflight in the Skylab 3 and Skylab 4 crewmen (21). This hyperactivity could have resulted in overreaction and overcompensation on the part of the crewman, thus making rail performance difficult.

The fourth mechanism that could be responsible for the degradation of postural stability observed postflight in the Skylab crewmen is one which would include as contributing factors all of the possibilities mentioned. Once the pattern center serving the postural, mechanicomotor system has been established in weightless and must begin habituation to a one-g reference, increased reflex sensitivity may be only one aspect of the process. A second aspect may be that the loss of tissue volume would contribute to a reduction in mechanical damping of leg movements. For example, if we look at the pattern center serving the postural, mechanicomotor system as one in which control depends on negative feedback (as the muscle spindle control system does), then it is possible for instability to occur both in locomotion and postural equilibrium. The instability results because the error signal takes time to generate a corrective response. This means that, if no compensation for the error is programed, the corrective signal would arrive at such a time that the leg, in this case, has already moved on to a new position. A second correction would be necessary which would also result in overshooting. To stop this oscillation around the desired point, the limb movement must be damped. Pure mechanical damping is provided by the in-series elastic elements in the muscles as well as the viscosity of muscle tissue and joints (22). More tissue in the leg adds increased mechanical damping while less tissue would tend to permit underdamped movements.

An alternate way of viewing damping is to suggest that the reflex control system depends on an output determining both position error and the rate-of-change of muscle length. When the system has rate-of-change information available, anticipation of the new limb position is predictable and a corrective signal can be initiated to begin

corrective adjustment (23). The hyperreflex activity observed could be a compensatory reaction generated in the mechanism responsible for programing the position center as a result of modified otolith input and a mechanically underdamped system.

Our results tend to support this fourth hypothesized mechanism. Decreased postural stability was observed in all crewmen when tested postflight. Although the larger deficits were obtained when visual cues were not available, there were greater changes in postflight equilibrium in the Skylab 3 crew with vision than there were in the Skylab 4 crew. Correspondingly, the Skylab 3 crew did not exercise to the same degree in-flight as the Skylab crew and, as a result, exhibited a greater loss in leg muscle strength and muscle tissue. This suggests that vision compensated less with increasing muscle mass loss.

These overall findings argue for an environment dependent memory store (pattern center) of frequently repeated sensory inputs that is under the guidance of a combined otolith, kinesthetic, and touch system which registers the actual movement and allows for anticipation and compensation of each movement as it occurs. Being environmentally dependent, such a mechanism could account for the buildup of postural responses (such as hyperreflex activity) in zero-g that would be inappropriate upon return to a one-g reference. A mechanism of this type could be applied to account for sensory physiological habituation in a variety of situations. In particular, such a mechanism could provide an adequate basis for change when the acquired response patterns are no longer congruent with the environment.

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SKYLAB SLEEP MONITORING EXPERIMENT (M133)

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ABSTRACT

Astronauts on pre-Skylab missions commonly complained of insomnia, and in some cases periods of sleep loss degraded crew performance. Investigation of this situation was important in planning future long-term flights. Subsequently, the first objective measurements of man's ability to obtain adequate sleep during prolonged space flight were made during the three manned Skylab missions.

Electroencephalographic, electro-oculographic, and head-motion signals were acquired during sleep by use of an elastic recording cap containing sponge electrodes and an attached miniature preamplifier/accelerometer unit. A control-panel assembly, mounted in the sleep compartment, tested electrodes, preserved analog signals, and automatically analyzed data in real time (providing a telemetered indication of sleep stage).

One subject was studied during each manned mission, and, while there was considerable variation among individuals, several characteristics were common to all three: stage 3 sleep increased during the flight and decreased in the postflight period; stage 4 was consistently decreased postflight, although this stage was variable during the flight; stage REM (rapid eye movement) was elevated, and REM latency decreased in the late postflight period (after day three post recovery); and the number of awakenings during sleep either showed no change or decreased during the flight.

In only the 28-day mission (Skylab 2) was there a significant decrease in total sleep time; in that case it was a result of voluntarily reduced rest time and was not due to difficulty in sleeping nor frequent

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awakening. The subject on the 84-day mission (Skylab 4) experienced some difficulty in the first half of the flight, showing a decreased total sleep time and increased sleep latency, but this resolved itself with time. Sleep latency presented no problem in the other flights. While many of the findings are statistically significant, in no case would they be expected to produce a noticeable decrement of performance capability.

These findings suggest that men are able to obtain adequate sleep in regularly scheduled eight-hour rest periods during extended space flights. It seems likely, based upon these results, that the problems encountered in earlier space flights did not arise from the zero-g environment *per se*, but possibly they were a result of more restricted living and working areas in the pre-Skylab spacecraft.

INTRODUCTION

Prior to Skylab, very little objective information had been obtained concerning man's ability to sleep in space. Only by continuous electroencephalographic monitoring can such information be obtained, and the technical problems associated with acquisition and analysis in space are significant. Before the advent of manned space flight, there was some concern about the possible adverse effects of this weightless environment upon sleep characteristics (1). During the Gemini program, however, it became apparent that fairly long duration space flight was not associated with drastic alterations of sleeping behavior. Astronauts could sleep in space and, on at least some occasions, did so fairly well. In the Gemini and Apollo programs, though, it became clear that in many instances insomnia was a problem. Sleep loss, while not absolute, was apparently sufficient in some instances to result in performance decrements. In several instances, sleeping difficulties resulted in the use of hypnotic drugs to promote sleep and an amphetamine-type medication to increase alertness following sleep loss.

It has long been recognized that sleep deprivation is associated with degradation of performance, the amount or severity of the performance decrement generally increasing in proportion to the length of the sleep loss (2). Since crew members are expected to perform at a high level throughout a mission, their ability to obtain sufficient sleep becomes an important variable in terms of overall mission planning and scheduling of daily work-rest periods.

The United States' first attempt to record the electroencephalogram during space flight was carried out during the Gemini 7 mission in 1965 (3-6). Technical difficulties associated with electrode

attachment limited recording to slightly under 55 hours. However, two sleep periods were observed, and, while the first was found to be inadequate in terms of duration and quality, the second was considered to be normal. Postflight examination of the recorded electronencephalogram showed no pathological changes or definite alterations attributable to weightlessness. The limited nature of this recording precluded an adequate analysis of sleep characteristics during long-term space flight; consequently, the purpose of the Skylab M133 sleep monitoring experiment was to obtain the first truly objective evaluation of man's ability to sleep during extended space travel.

The Skylab astronauts carried out a wide varity of work during the three missions, accomplishing numerous research projects in the physical and biomedical sciences. The working volume of the Skylab orbiting laboratory was over 12 000 cubic feet (comparable to a moderate-sized house), with adequate space to provide separate facilities for work, recreation, meals, and sleep. The crews maintained a 24-hour schedule based upon Central Standard Time, to which they were accustomed on the ground. At an altitude of approximately 270 statute miles, Skylab circled the earth approximately every 93 minutes.

Each astronaut had his own sleeping compartment, which was equipped with a sleep-restraint system quite similar in appearance and function to a sleeping bag. An eight-hour rest period was typically scheduled between 10 p.m. and 6 a.m. for all three crewmembers, although variations in this protocol were occasionally necessitated by specific work requirements.

Sleep was studied in an objective manner on three of the Skylab astronauts, one each during the 28-, 59-, and 84-day missions.

METHODS

The complete sleep-analysis system designed for this experiment included data-acquisition hardware, onboard analysis components, and a capability for real-time telemetry.

Onboard equipment accomplished automatic analysis of the electroencephalogram, electro-oculogram, and head-motion signals. The system's output, consisting of sleep-stage information, was telemetered in near real time to Mission Control, where a profile of sleep state versus time was accumulated. The analog signals (electroencephalographic, electro-oculographic, and head motion) were also preserved by onboard magnetic-tape recorders, thus allowing a more detailed post flight analysis.

Flight Hardware

The components for the hardware are shown in figure 1. The astronaut wore a recording cap containing electrodes for detecting electroencephalographic and electro-oculographic activity. A preamplification unit, attached to the cap near the vertex of the head, amplified the signals, and a dual-axis accelerometer, housed within the preamplifier, provided information concerning movement of the subject's head. A flexible cable connected the preamplifier with a control-panel assembly mounted on the wall in the subject's sleep compartment. Within the control-panel assembly, additional circuitry accomplished automatic electrode testing, sleep analysis, and generation of the telemetry output signal, indicative of the subject's current level of consciousness. Two tape recorders, attached to the rear of the control-panel assembly, provided an analog record of the subject's sleep.

The methodology has been extensively described in prior publications (7-10) and will be reviewed only briefly below.

The recording cap (fig. 2), made of an elastic-type fabric, stretches to conform comfortably to the subject's head. Inside the cap, sponge-type electrodes are attached at the positions necessary for acquisition of electroencephalographic and electro-oculographic signals; wires join the electrodes to a miniature electrical connector at the vertex of the cap, enabling rapid linkage with the preamplifier/accelerometer assembly. The cap contains seven electrodes, arranged such that four electrodes (left and right central positions, C_1 and C_2, and left and right occipital positions, O_1 and O_2) provide a composite electroencephalogram channel (C_1 and C_2 paired together and referred to O_1 and O_2 paired); two electrodes provide one electro-oculogram channel (one electrode lateral to, and one above, the left eye); while the seventh electrode serves as a ground.

The electrodes are prefilled with a gelled, conductive electrolyte; then the cap is stored in a plastic bag until needed. The donning procedure requires less than five minutes of the subject's time prior to retiring, and, since each cap is used only once, post recording breakdown is limited to removal of the cap, disconnection of the preamplifier/accelerometer unit, and disposal of the cap.

The small, lightweight, preamplifier/accelerometer unit contains electroencephalographic and electro-oculographic preamplifiers (the gain is approximately six), electroshock-protection circuitry, and dual-axis accelerometers for detecting the subject's head motion in the

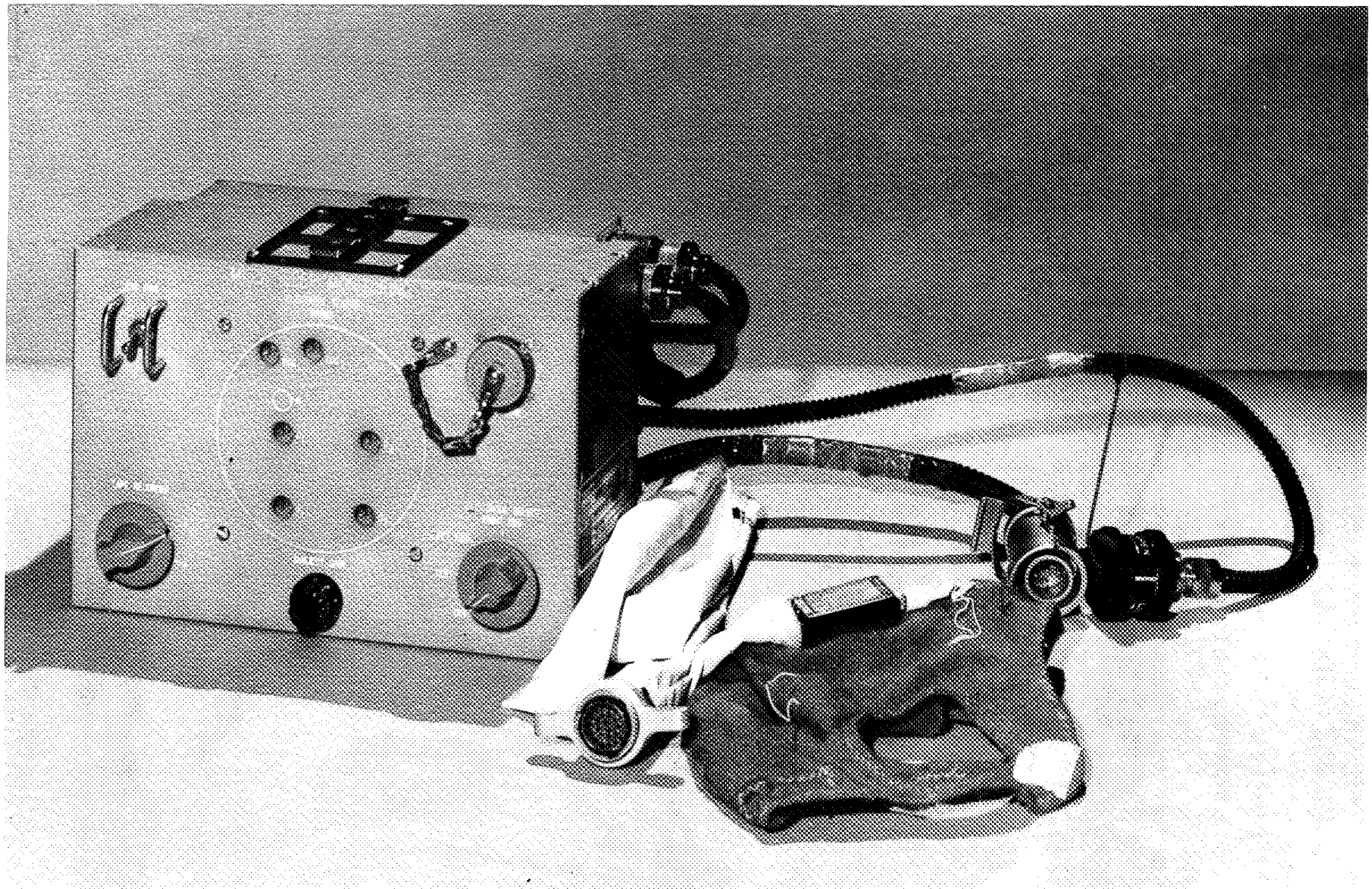

Figure 1. Skylab M133 sleep monitoring experiment hardware: control-panel assembly (left) recording cap and preamplifier unit (lower right).

Figure 2. Scientist Pilot, 59-day mission, in his sleep restraint.

lateral (side-to-side) and vertical (up-down) axes. The amplified signals pass through the flexible cable to the control-panel assembly, which provides final amplification.

The preamplifier/accelerometer unit quickly attaches to the cap at the vertex, using a Velcro patch; an electrical connector provides electrical continuity with the electrodes.

The control-panel assembly, mounted on the wall of the sleeping compartment, is within easy reach of the sleep restraint.

At bedtime, after the astronaut dons the recording cap, each electrode is automatically tested to insure proper function. The control-panel front, easily visible from the sleep restraint, contains indicator lamps arranged in a configuration simulating the position of the recording electrodes on the head. As the astronaut activates the test circuit, a small current (approximately $10 \mu A$) passes in succession through the single ground electrode to each of the recording electrodes. In this manner, interelectrode resistance is determined; if a given electrode has achieved proper scalp contact (resistance $50\,000\ \Omega$ or less), the lamp corresponding to that electrode is illuminated. Improper contact is indicated by the failure of a lamp to illuminate, and the subject corrects this by gently rocking the electrode in question from side to side to position the tip through the hair.

Continuous monitoring of electroencephalographic, electro-oculographic, and head motion signals is done during the sleep period. Following final amplification within the control-panel assembly, the signals proceed to data-analysis circuitry and to analog magnetic-tape recorders. Two recording units compose the analog recording system, each unit's storage capacity being up to 150 hours of data.

As the monitoring sessions progress, the data-analysis circuitry within the control-panel assembly supplies sleep-stage information in near real time to observers in Mission Control. Onboard, the electroencephalographic, electro-oculographic, and head-motion signals are processed in real time. Electroencephalographic signals alone determine stages Awake, 1, 2, 3, and 4 of sleep; electroencephalographic and electro-oculographic signals differentiate stage REM. Signals likely to be contaminated by artifacts do not reach the analysis section, since the electroencephalographic and accelerometer circuits specifically exclude them.

Automatic electroencephalogram analysis is based upon the decline in frequency and the general increase in amplitude seen as an individual progresses from the awake state to stage 4 sleep — criteria very

similar to those used in visual scoring techniques. Initial filtering limits further consideration of the single electroencephalographic channel to 0.7-13 Hz activity. The filtered signal then enters an amplitude-weighted frequency-meter circuit with a varying d.c. level output: it is highest when the input signal is intermediate in amplitude and high in frequency, and it is lowest when the input is high in amplitude and low in frequency.

In consequence, this signal is proportional to sleep states encompassing Awake to stage 4, the highest output value being associated with the waking state. A series of comparator circuits sense this voltage and compare it to previously determined voltage ranges, each range corresponding to one of the clinical sleep stages. So, while the output remains within the parameters designated for a given sleep stage, a constant indication of that stage flows to the final output logic of the system.

The electroencephalographic-analysis circuitry cannot distinguish stage REM, and, because of its similarity in frequency and amplitude to stage 1 or 2, the circuitry typically regards it as one or the other. Additional circuitry monitoring the single electro-oculographic channel detects events resembling rapid eye motion. Certain electro-oculographic events, such as K-complexes, may develop in the electro-oculographic channel and mimic real eye movements, and these are recognized and excluded from further consideration. Other circuits use electroencephalographic and head-motion signals to prevent signals with high probability of artifactual contamination from influencing the electroencephalographic and electro-oculographic sleep-determination circuits. The final output-logic scheme combines outputs from the electroencephalographic, electro-oculographic, and artifact-detection circuitry into a single value representing one of the possible sleep states and supplies it continuously to the spacecraft telemetry. Stage REM is indicated if periods of rapid eye movement coincide with an electroencephalographic-section output indicating either stage 1 or 2. Rapid eye movements occurring in other stages are ignored, and the electroencephalographic-section output alone is accepted.

Thus, the analysis-circuitry output continuously displays one of seven possible states: Awake; stage 1 through 4 and REM of sleep; or stage 0, indicating the absence of adequate data. This output, essentially a three-bit code, arrives at Mission Control in real time as the spacecraft passes over tracking stations. Between stations, the digital signals are recorded onboard and then transmitted at a high rate during a subsequent tracking-station pass.

Ground-Based Data Analysis

During a sleep monitoring session, true real-time data was available only during the few minutes when the spacecraft was passing over a ground tracking station. Throughout the frequent periods when the spacecraft was out of communication range, the spacecraft telemetry recorder accumulated sleep-stage data and transmitted it to the ground at a high rate during a subsequent tracking-station pass. The tracking stations, in turn, relayed the information to Mission Control. Consequently, the data ultimately received during a sleep period was somewhat sporadic, ranging from actual real time to delays of up to several hours. Data-processing equipment in Mission Control collated the incoming data so that the time relationships were preserved, and eventually a complete tabulation of sleep state versus elapsed time evolved.

Although data was telemetered at a rate of 1.25 sleep-stage samples per second (75 samples per minute), a subject's sleep stage does not typically change more often than two or three times each minute, and it is often stable for several minutes. The data-processing system was therefore programmed to indicate only the time and the sleep stage when a change of sleep level occurred. The resultant listing of sleep-stage information versus time was transferred to The Methodist Hospital, where the computer facilities of the Neurophysiology Laboratory and the Baylor Institute of Computer Science were employed to provide the final data analysis.

The end product was a compact graphic plot showing the complete profile of sleep stage versus time over the course of a sleep period. The data was displayed at a horizontal resolution of approximately 5 centimeters per hour, with a vertical span of approximately 10 centimeters, thereby providing an observer with an overall summary or profile of the sleep period (see example, fig. 3). A statistical summary of the all-night data was also supplied for each sleep period, and values for the following parameters were included: total rest-period time, total sleep time, total awake time, sleep latency, number of arousals, accumulated time in each sleep stage, percentage of total sleep time occupied by each sleep stage, and REM latency.

At the conclusion of each Skylab mission, the onboard data tapes were returned by the crew, and this data was then analyzed by conventional visual scoring techniques (11) after playback onto a graphic recorder.

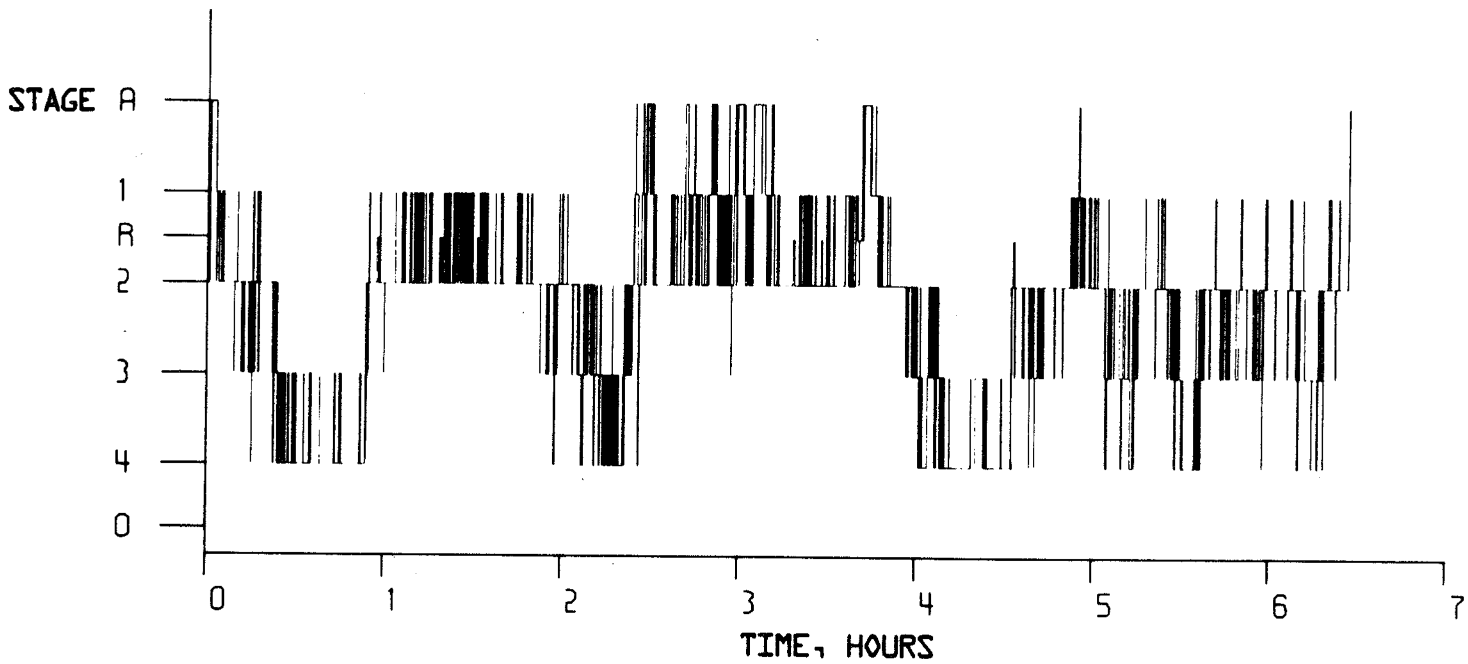

Figure 3. Sleep plot generated by computer: Scientist Pilot, day 21 of the 28-day mission.

Experimental Design

One crewmember participated in the sleep monitoring activities during each Skylab flight. Baseline data was obtained on the participating subjects before flight during three consecutive nights of sleep monitoring, using portable apparatus functionally identical to the onboard hardware. The astronaut studied during the 28-day mission was recorded in his own home two months prior to launch, while the subjects of the 59- and 84-day missions were monitored in the preflight quarantine facility two weeks before their respective launches. In addition, a standard clinical electroencephalogram was performed on each subject prior to the flight to permit precise electroencephalographic amplitude determinations for calibration of the flight hardware.

Monitoring during flight was accomplished during 12 selected nights of the 28-day mission (nights 5, 6, 7, 10, 11, 15, 17, 19, 21, 24, 25, and 26), during 20 nights of the 59-day mission (nights 7, 8, 9, 12, 15, 18, 21, 24, 27, 29, 33, 36, 39, 42, 45, 48, 52, 55, 56, and 57), and during 18 nights of the 84-day flight (nights 3, 4, 10, 14, 19, 24, 29, 34, 40, 45, 50, 55, 60, 72, 77, 80, 81, and 82). Operational factors associated with the activation and function of various spacecraft systems prevented recordings during the initial period of each flight.

Crew bedtime was typically 2200 hours d.s.t., and the scheduled sleep period terminated at 0600 hours d.s.t., although occasional deviations from this schedule were necessitated by work requirements not associated with the sleep monitoring experiment. During the last week of the 28- and 59-day missions, sleeping schedules were adjusted forward by a total of four hours (*i.e.*, typical bedtime became 1800 hours d.s.t.). An adjustment of two hours was made on days 20 and 22 of the 28-day mission, and there was a similar change of two hours on days 51 and 53 of the 59-day mission. During the 84-day mission, schedule alterations were made during the last three days only, and consequently only one day (day 82) of sleep monitoring was affected. On this day, the bedtime was advanced approximately two hours (approximately 2000 hours d.s.t.), and the subject was permitted a 10-hour total rest time (*i.e.*, the time of awakening remained approximately 0600 hours d.s.t.). These scheduled alterations were necessitated by the activities associated with splashdown and recovery operations, which required early awakening on the final day of the mission.

Upon return to Earth, postflight baseline studies were performed on each sleep monitoring participant. After the 28-day mission, recordings were done on nights 4, 6, 8, and in the case of the 59-day

mission, on the second, fourth, and sixth nights following splashdown. Following the 84-day flight, recordings were made on the first, second, and fifth nights.

Operational Factors

A period of elevated temperature, present in the Skylab workshop prior to the arrival of the first crew (an effect of loss of a portion of the solar heat shield during launch), resulted in two problems with respect to the sleep monitoring activities scheduled for the first manned mission. Several recording-cap electrodes suffered partial dehydration, and as a result most of the data were lost during one scheduled recording night. In addition, the analog-tape recording system was damaged, and only two nights were successfully recorded.

The recording-cap problem necessitated the use during the first (28-day) mission of caps intended for subsequent flights, which had been stored onboard the spacecraft in a location that remained cooler during the period of elevated temperature.

The crew of the second manned Skylab mission (59 days) took a repair kit to refurbish the damaged recording caps by injection of supplementary electrolyte gel prior to use. In addition, repair of the recording system was attempted prior to the first night of recording. These steps were generally successful, although one additional night was lost during the 59-day mission due to recording-cap problems, and six nights of tape-recorded data were lost near the end of the mission when the recording system again failed.

Prior to launch of the Skylab workshop, the plan was to monitor sleep during only the first and second manned missions, so just enough recording caps were placed aboard to provide one for each scheduled night. When the schedule was later changed to include sleep monitoring on the final, or 84-day, flight, there were not enough caps remaining to permit use of a new unit for each recording session. Instead, the subject reused a cap several times and injected additional electrolyte gel into the sponge electrodes before donning the cap each night. This technique was satisfactory, and the data quality remained high. Of the 18 sessions attempted during the 84-day mission, 17 were successfully accomplished. One night (night 50) was lost when power to the onboard hardware was lost after approximately two hours of recording. A significant data loss also occurred on two additional nights of the 28-day mission and on one other night of the 59-day mission, stemming from ground-based problems in the data-processing system.

Despite the unforeseen problems, however, successful near-real-time monitoring was accomplished on 9 of the 12 attempted recording nights during the 28-day mission, on 18 of the 20 nights attempted on the 59-day mission, and on 17 of the 18 attempted sessions of the 84-day mission. Postflight return of the analog tapes permitted visual confirmation of the results on 2 of the 9 nights of the 28-day mission, on 12 of the 18 nights of the 59-day mission, and on 17 of the 18 nights of the 84-day mission.

STATISTICAL ANALYSIS

The final results described below represent the best available estimates of the various sleep parameters. The results are, when possible, those obtained by visual analysis of the tape-recorded electroencephalographic, electro-oculographic, and head-motion signals, since this method is considered the most reliable and the least influenced by various artifactual components that may be present. In the instances where this was not possible due to loss of recorded data on several nights, the results of onboard automatic analysis have been utilized after application of certain corrective factors based upon past performance of the system and, in the case of the 59-day mission, upon correlation of the results during flight with those of visual analysis for the nights on which both types of information were available.

Modification of Automatic-Analysis Results

The uncorrected results of automatic analysis consistently underestimate stage REM sleep. This occurs because the criteria for continuous stage REM indication used by the automatic system include the occurrence of at least one detectable rapid eye motion per 30-second time epoch. If such an eye motion does not occur, the output will revert to stage 1 or 2, as determined by electroencephalographic criteria alone. In most individuals, true stage REM occasionally occurs for periods longer than 30 seconds in the absence of eye motion of sufficient amplitude to be detected by the automatic circuitry. Typically, then, the output of the automatic system during a continuous stage REM period is a fluctuation between stages 1, REM, and 2. Such periods usually are readily identified by inspection of the plotted sleep profile (fig. 3). When the automatic data is modified by the assignment to stage REM of all time within such a period, the overall results are significantly enhanced. Such modification introduces an element of subjectivity into otherwise objective data; however, we believe this is justified in this case, since past experience has confirmed its validity.

Other than eliminating certain obviously artifactual sections of data (*e.g.,* sections near the start of each sleep period associated with cap donning and electrode-testing procedures), the REM-modification step (MA, table I) was the only corrective factor instituted during the in-flight portions of the Skylab missions.

Reliability of Automatic-Analysis Results

After the 59-day mission, we compared the results of modified in-flight analysis with those of visual analysis of the taped data for 11 of the first 12 recording nights. The average (mean) error of automatic analysis based upon visually determined total rest-period time was as follows: total rest-period time, +1 percent; total sleep time, +4 percent; sleep latency, -0.3 percent. The average (mean) error of automatic analysis in sleep-stage determination (as compared to the same visually determined parameter) was as follows: stage 1, +5.6 percent; stage 2, -0.4 percent; stage 3, -10.6 percent; stage 4, -0.7 percent; and stage REM, +6.1 percent.

In most cases, then, automatic analysis gave satisfactory estimates of the actual value. The worst case, percent of stage 3 sleep, was apparently a result of the particular subject's sleeping pattern, in which a large proportion of the misclassified epochs were borderline in terms of stage 2 versus stage 3. The underestimation was consistent throughtout all 11 comparison nights. The stage REM overestimation, on the other hand, was not consistent and appeared to result solely from the inherent limitations of the automatic-analsysis scheme in detecting this stage and in rejecting certain artifacts.

Similar comparisons between visual and automatic analysis were made following the 84-day flight for the 17 successful monitoring sessions. In this case, the average (mean) error of automatic analysis compared to the visually determined total rest-period time was as follows: total rest-period time, +1.2 percent; total sleep time, +4.4 percent; sleep latency, +0.9 percent. The average error of automatic analysis in sleep-stage determination (as compared to the visually determined parameter) was as follows: stage 1, +1.6 percent; stage 2, -11.4 percent; stage 3, +7.9 percent; stage 4, +6.1 percent; and stage REM, -4.2 percent.

Correlation and Regression Techniques

Regression analysis, after correlation of automatic and visual results, provided a means for further modifying the results of automatic analysis (MCA, table II) for those six nights of the 59-day mission unconfirmed by visual analysis (*i.e.,* nights 42, 45, 48, 52, 56, and 57, for which the analog-tape data was lost).

TABLE I

28 - DAY MISSION

	PREFLIGHT			AVG.		IN - FLIGHT									AVG		POSTFLIGHT			AVG
MISSION DAY	-60	-59	-58			5	6	10	15	17	19	21	24	26			+3	+5	+7	
ANALYSIS TYPE	V	V	V			V	V	MA	MA	MA	MA	MA	MA	MA			V	V	V	
TOTAL REST TIME	7.3	7.3	8.7	7.8		6.6	6.3	7.7	7.4	5.6	7.7	6.5	8.0	6.0	6.86		9.3	9.0	8.5	8.9
TOTAL SLEEP TIME	6.5	6.5	7.7	6.9		6.1	5.4	5.3	7.0	5.2	6.6	6.2	7.2	5.4	6.04		9.0	8.5	8.0	8.5
TOTAL AWAKE TIME	0.74	0.81	0.96	0.84		0.31	0.85	2.43	0.45	0.47	0.81	0.25	0.67	0.26	0.72		0.26	0.45	0.44	0.38
SLEEP LATENCY	0.46	0.70	0.73	0.63		0.35	0.33	0.28	0.35	0.18	0.76	0.06	0.10	0.30	0.30		0.17	0.24	0.16	0.19
STAGE 1 (%)	7.4	4.3	4.2	5.3		6.8	9.5	9.8	8.3	7.7	1.1	5.4	4.4	0.6	5.95		4.0	6.5	4.8	5.1
STAGE 2 (%)	60.3	49.6	54.5	54.8		60.2	56.4	43.4	56.4	26.7	50.9	43.8	28.9	24.0	43.4		58.5	53.8	57.4	56.6
STAGE 3 (%)	12.8	17.9	13.8	14.8		18.3	14.6	10.0	12.6	8.8	13.1	11.2	28.0	27.8	16.0		11.8	11.1	13.7	12.2
STAGE 4 (%)	2.9	3.4	2.4	2.9		4.6	0.8	12.6	17.1	14.9	14.5	16.5	27.7	41.6	16.7		1.0	1.0	1.3	1.1
STAGE REM (%)	16.6	24.8	25.1	22.2		10.1	18.6	24.1	5.5	41.9	20.4	23.2	11.0	5.9	17.9		24.7	27.5	22.8	25.0
REM LATENCY	1.24	1.24	1.91	1.46		2.31	1.66								1.98		0.93	1.18	1.11	1.07
NO. OF AWAKENINGS	19	16	24	19.7		10	14								12		20	20	26	22

TABLE II

59 - DAY - MISSION

	PREFLIGHT			AVG.		IN-FLIGHT																				AVG.		POSTFLIGHT			AVG
MISSION DAY	-15	-14	-13			7	8	9	12	15	18	21	24	27	29	33	36	39	42	45	48	52	55	56	57			+1	+3	+5	
ANALYSIS TYPE	V	V	V	V		V	V	V	V	V	V	V	V	V	V	V	V	$^{M}C_{A}$	$^{M}C_{A}$	$^{M}C_{A}$	$^{M}C_{A}$	$^{M}C_{A}$	$^{M}C_{A}$	$^{M}C_{A}$	$^{M}C_{A}$			V	V	V	
TOTAL REST TIME	7.7	8.4	6.5	7.5		6.90	6.59	8.23	7.14	7.32	7.05	6.95	7.27	7.87	8.90	7.19	7.38	7.21	7.23	7.55	7.68	6.82	6.78	7.32	6.61	7.32			7.09	8.44	7.77
TOTAL SLEEP TIME	6.4	7.6	5.2	6.4		5.95	6.08	6.94	6.24	6.86	5.75	5.47	6.50	7.03	6.96	6.46	6.99		6.16	6.47	6.14	5.04		6.48	6.44	6.31			5.77	7.38	6.58
TOTAL AWAKE TIME	1.3	0.8	1.3	1.1		0.95	0.51	1.28	0.90	0.46	1.30	1.49	0.77	0.87	1.94	0.73	0.38		1.07	1.08	1.54	1.78		0.84	0.17	1.00			1.32	1.06	1.19
SLEEP LATENCY	0.3	0.09	0.2	0.2		0.21	0.24	0.32	0.32	0.13	0.15	0.06	0.15	0.26	0.36	0.19	0.12		0.14	0.37	0.12	0.36	0.10	0.16	0.17	0.21		0.08	0.15	0.24	0.16
STAGE 1 (%)	8.3	7.6	10.6	8.8		7.5	5.9	11.2	10.6	8.7	11.9	11.6	9.5	11.3	13.5	4.3	5.0		7.5	9.4	10.5	7.3		6.4	8.8	8.9			10.4	9.9	10.2
STAGE 2 (%)	57.3	58.3	53.3	56.3		59.5	57.4	63.2	60.4	60.7	57.8	49.2	62.4	63.6	56.6	60.8	59.1		61.0	60.5	59.6	60.9		61.0	60.1	59.7			57.1	58.4	57.8
STAGE 3 (%)	18.0	16.4	17.7	17.4		19.1	13.5	13.8	17.2	18.6	15.8	24.6	13.9	15.1	20.0	19.1	19.4		15.4	17.9	16.2	16.6		17.4	21.1	17.5			12.0	8.2	10.1
STAGE 4 (%)	3.1	4.9	0.3	2.8		1.8	1.9	0.8	1.6	1.5	1.0	3.1	1.3	0.8	1.3	1.1	1.4		1.3	1.3	1.3	1.3		1.3	1.3	1.4			0.4	0.4	0.4
STAGE REM (%)	13.2	12.7	18.2	14.7		12.1	21.3	11.0	10.2	10.7	13.4	11.5	13.0	9.2	8.6	14.7	15.1		11.8	13.2		10.8		8.5	10.1	12.1			20.1	23.0	21.6
REM LATENCY	1.6	2.2	1.8	1.87		1.5	1.8	2.3	2.6	2.2	2.1	1.6	2.2	2.3	2.9	1.6	1.6		2.0							2.05		0.8	1.1	0.7	0.87
NO. OF AWAKENINGS	37	51	34	40.7		39	32	70	52	62	43	21	51	44	25	8	25									39.3			26	31	28.5

As noted above, the overall correlation between visual and automatic results for stage REM percentage was low and consequently could not be utilized for reliable prediction of the remaining six values. However, it was determined that stage REM values below 20 percent, as indicated by automatic analysis, were better correlated with visual results; consequently, regression analysis for this stage was based upon correlations of only 6 of the 11 nights (discarding nights 7, 8, 9, 12, and 29). Corrected REM values were thus predicted for 5 of the 6 remaining nights, discarding the value (30.4 percent) for day 48, which exceeded 20 percent.

These statistical maneuvers provided a consistent means for utilizing all the available information. The values obtained are included in the results presented below and were subjected to further statistical analysis along with the visual-analysis results, although it was determined that the overall significance of the results was the same, whether or not these values were included.

Analysis of Variance

Finally, for each mission, preflight, in-flight, and postflight conditions for each parameter were treated by an analysis of variance. *A posteriori* comparisons were made in cases where the overall F test reached conventional levels of statistical significance($P < 0.05$).

In summary, with respect to the final results outlined below, of the 9 nights recorded during the 28-day mission, only the first 2 are based upon visual analysis. The remainder are based upon the modified results of automatic analysis. For the 59-day mission, the results of the first 12 nights are based upon visual analysis, while the last 6 are automatic results modified both in-flight in terms of REM time and postflight by the application of corrective factors based upon visual/automatic comparison of the first 12 nights. For the 84-day mission, all 17 nights are based upon the results of visual analysis.

Data Quality

Data quality, as evaluated by visual inspection of the signals played back from the analog tapes returned at the conclusion of each mission, was generally excellent. Although recorder malfunctions occurred during the 28- and 59-day missions, the data recorded prior to the failures were, in both instances, of high quality. During the 84-day mission, the recorded signals were of clinical quality throughout.

Selected examples of the electroencephalographic, electro-oculographic, and head-motion signals, as played back from the onboard tapes, are shown in figures 4 through 6. Figure 4 illustrates the transition from the awake, alert state through the various stages of sleep for the Scientist Pilot on day 6 of the 28-day mission. A similar series for the subject of the 59-day mission is illustrated in figure 5, which were obtained during day 29. Examples from day 3 of the 84-day mission are shown in figure 6.

RESULTS

Sleep Latency

The amount of elapsed time from the actual onset of the rest period until the first appearance of stage 2 sleep is defined as sleep latency. Sleep-latency characteristics observed during the three Skylab missions are summarized in figure 7 and tables I, II, and III. Average in-flight, preflight, and postflight figures for this parameter are indicated in the tables. Sleep latency varied considerably during the 28-day mission (fig. 7 part A), ranging from a low value of 3.6 minutes on day 21 to a maximum of 45 minutes on day 19. Day 19 was, however, the only instance in which the latency exceeded the preflight values, and the average in-flight value of 18 minutes actually represents a decrease of 20 minutes as compared to the preflight average of 37.8 minutes. Postflight values were all relatively low but well within the in-flight range. Statistically, the in-flight and postflight latencies were less than the preflight values ($P < 0.01$).

No statistically significant changes in sleep latency were noted during the 59-day mission, as indicated in figure 7 part B, although on several days the values were somewhat above the preflight average of 12 minutes. This parameter ranged from a low of 4 minutes on day 21 to a maximum of 24 minutes on day 45. A cyclic fluctuation of sleep latency was suggested, with maxima near days 10, 29, 45, and 52. The in-flight average value (12.6 minutes), however, was almost exactly the same as the preflight value. The postflight latencies, averaging 9.6 minutes, were only slightly less than either the preflight or in-flight measurements.

Sleep latency during the 84-day mission averaged almost the same in-flight (15.6 minutes) as preflight (16.2 minutes) but dropped to an average of 7.8 minutes postflight (table III). Although the averages do not reflect a significant change, inspection of figure 7 part C

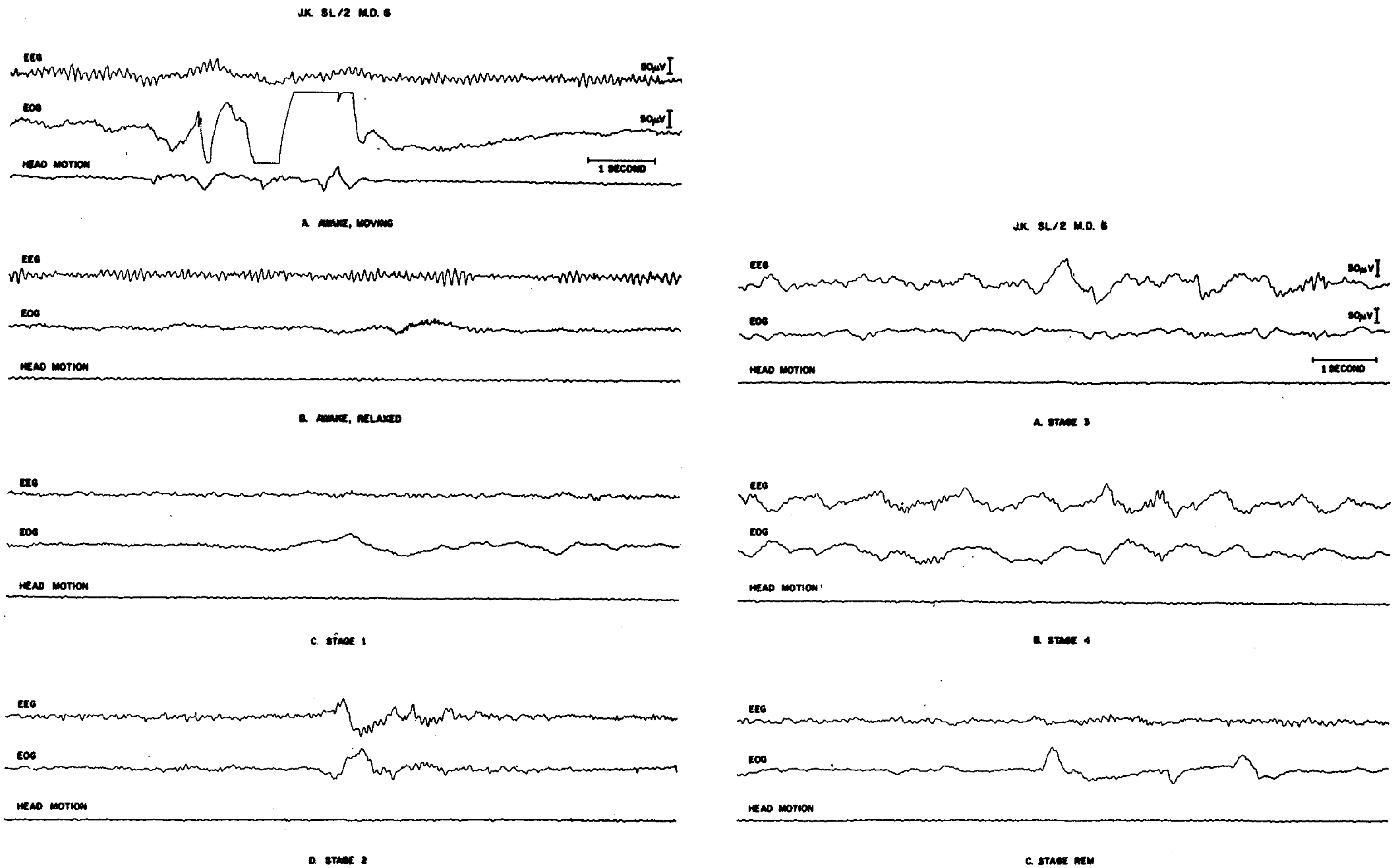

Figure 4. Examples of sleep recording, Scientist Pilot, day 6 of the 28-day mission.

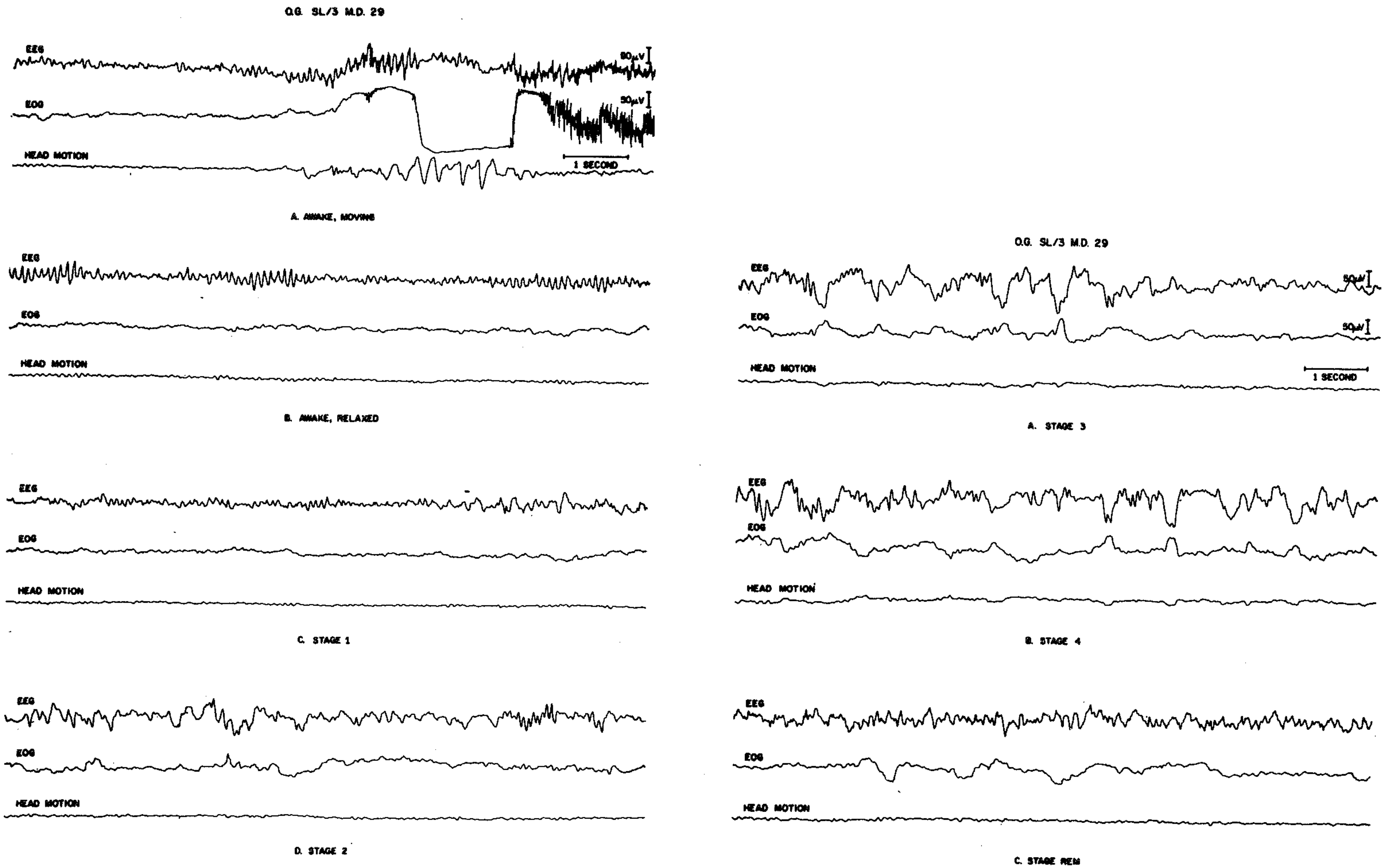

Figure 5. Examples of sleep recording, Scientist Pilot, day 29 of the 59-day mission.

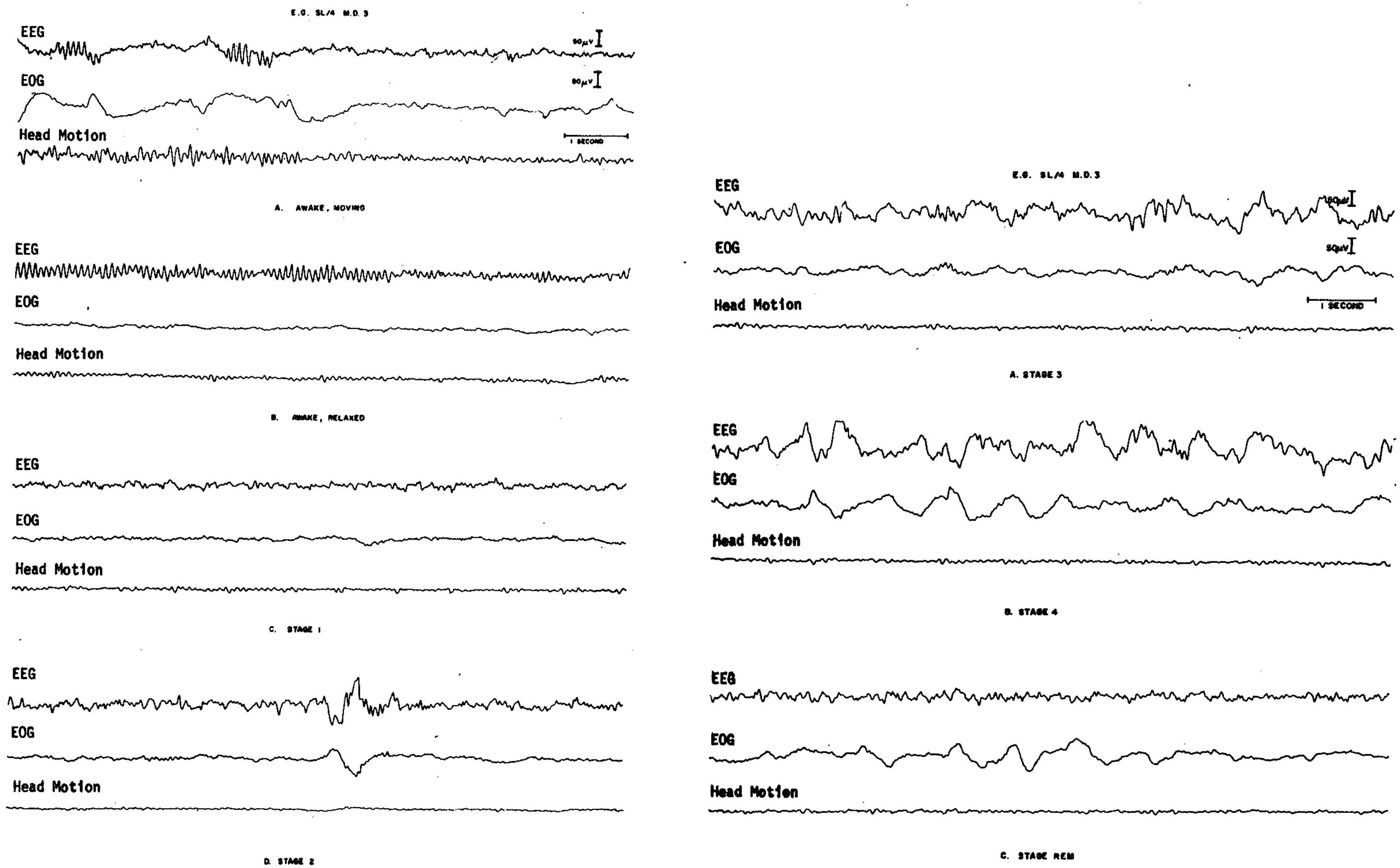

Figure 6. Examples of sleep recording, Scientist Pilot, day 3 of the 84-day mission.

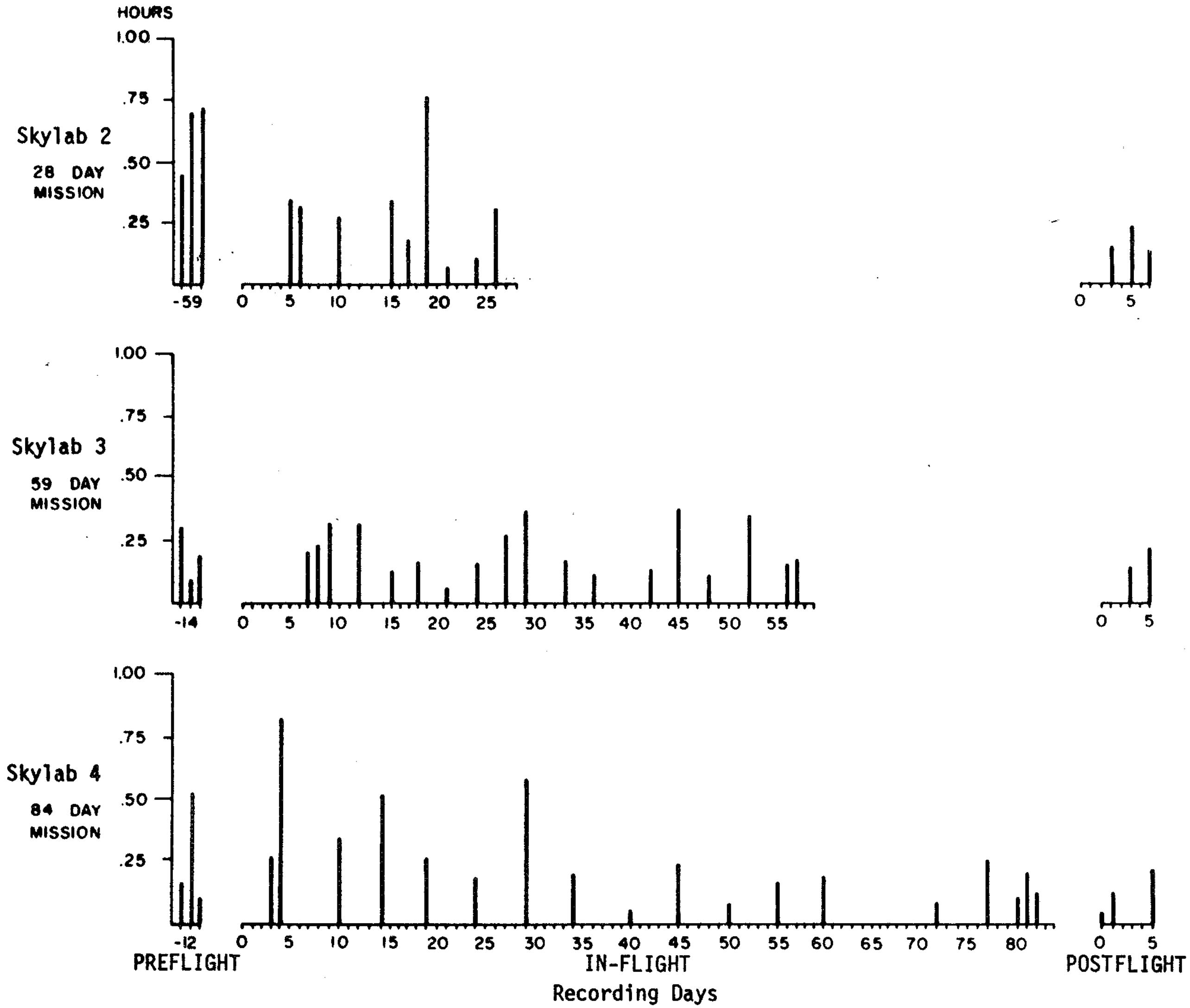

Figure 7. Sleep latency, all three Skylab missions.

TABLE III

84-DAY MISSION

	PREFLIGHT			AVG		IN-FLIGHT																		AVG		POSTFLIGHT			AVG
MISSION DAY	-13	-12	-11			3	4	10	14	19	24	29	34	40	45	50	55	60	72	77	80	81	82			+0	+1	+5	
ANALYSIS TYPE	V	V	V			V	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V			V	V	V	
TOTAL REST TIME	7.43	8.11	8.64	8.06		6.51	6.82	6.40	7.30	7.28	9.78	6.92	8.33	7.67	6.49		8.65	6.73	6.69	8.60	7.32	7.21	9.82	7.56		8.67	6.25	8.09	7.67
TOTAL SLEEP TIME	6.59	7.43	7.85	7.29		5.90	4.88	6.00	6.65	5.93	9.37	6.26	6.83	7.49	6.16		8.39	6.43	6.29	7.38	5.43	5.58	8.80	6.69		7.69	4.50	7.40	6.53
TOTAL AWAKE TIME	0.84	0.68	0.78	0.77		0.61	1.94	0.39	0.65	1.35	0.40	0.66	1.50	0.18	0.33		0.26	0.31	0.39	1.22	1.90	1.64	1.01	0.87		0.98	0.78	0.69	0.82
SLEEP LATENCY	0.16	0.55	0.10	0.27		0.26	0.82	0.33	0.53	0.26	0.18	0.59	0.20	0.04	0.24	0.08	0.14	0.19	0.09	0.27	0.11	0.22	0.12	0.26		0.04	0.13	0.23	0.13
STAGE 1 (%)	10.6	7.8	8.2	8.9		4.9	13.3	5.7	8.6	6.4	6.8	10.4	8.8	4.0	4.9		5.3	4.6	5.0	5.4	6.9	7.8	6.2	6.76		14.2	7.0	7.0	9.4
STAGE 2 (%)	59.5	54.1	62.0	58.5		57.3	50.2	58.4	61.4	50.8	56.1	54.3	50.9	65.5	65.0		53.8	61.6	66.8	61.8	60.7	58.0	62.5	58.5		71.5	71.1	55.8	66.1
STAGE 3 (%)	3.7	11.7	5.9	7.1		13.0	10.6	6.4	10.3	12.2	5.4	12.2	13.5	4.6	7.6		9.2	9.5	3.6	3.3	11.0	7.3	10.0	8.8		2.2	3.3	2.5	2.7
STAGE 4 (%)	0.0	0.4	0.1	0.2		1.2	0.5	0.2	0.6	1.3	0.1	1.6	1.5	0.1	0.4		0.2	0.5	0.04	0.0	0.5	0.1	0.3	0.5		0.0	0.1	0.04	0.05
STAGE REM (%)	26.2	26.0	23.8	25.3		23.6	25.4	29.3	19.2	29.4	31.6	21.4	25.2	25.7	22.1		31.6	23.8	24.5	29.5	20.9	26.8	20.9	25.3		12.1	18.6	34.6	21.8
REM LATENCY	0.96	2.45	1.01	1.47		1.24	0.12	0.79	0.95	1.15	1.03	1.19	2.22	1.11	1.08	1.49	0.84	2.55	1.23	1.13	1.17	1.01	3.34	1.31		2.68	0.79	0.90	1.46
NO. OF AWAKENINGS	20	21	21	20.7		10	8	15	15	13	20	12	16	14	6		22	6	6	8	12	11	10	12		21	11	24	18.7

reveals a preponderance of longer latencies in the first half of the mission and a decline as the flight progressed. The average value for the first half (days 3 through 40) was 21.4 minutes, while that for the latter half (days 45 through 82) was 9.7 minutes, a statistically significant difference ($P < 0.05$).

In general, then, there was no evidence of difficulty in falling asleep in either the 28- or 59-day mission, while in the 84-day mission, values somewhat above baseline were seen in the first half of the mission but declined to normal or below normal in the final portion.

Total Sleep Time

A commonly used measure of sleep adequacy is the total sleep time obtained in a given sleep period (*i.e.*, total rest-period time minus total time spent awake). Figure 8 illustrates the total rest-period length (overall amplitude of vertical bars), the total sleep time (solid portion of bars), and the total awake time (dashed portion of bars) for each Skylab recording night and for the preflight and postflight baseline studies.

It is apparent that in the 28-day mission (fig. 8 part A), there was a reduction in total sleep time throughout the in-flight period as compared to the preflight and postflight studies. Postflight, total sleep time was significantly greater than the preflight and in-flight values ($P < 0.05$ and 0.01, respectively). As indicated in table I, the in-flight average of 6.0 hours is almost one hour less than the preflight value of 6.9 hours and more than two hours less than the postflight average (8.5 hours). This decrease in sleep time, however, was due not to an unusual amount of time spent in the awake state but instead to a reduction in the total rest-period time itself. The subject thus slept quite well on most nights while he was in bed; however, he did not spend as much time in bed as he did during studies either before or after the mission.

The postflight average value for total rest-period time (8.9 hours) was significantly higher than the in-flight average ($P < 0.01$) but did not differ significantly from the preflight value.

No significant changes in the total sleep/total rest characteristics were obtained during the 59-day mission, as shown graphically in figure 8 part B. The total rest time (overall height of bars, fig. 8 part B), which averaged 7.3 hours in-flight (table II), was only slightly lower than either the preflight average of 7.5 hours or the postflight values of 7.8 hours. In terms of total sleep time (solid bars, fig. 8 part B) although there was considerable fluctuation, only one day (52) was below the range established during the

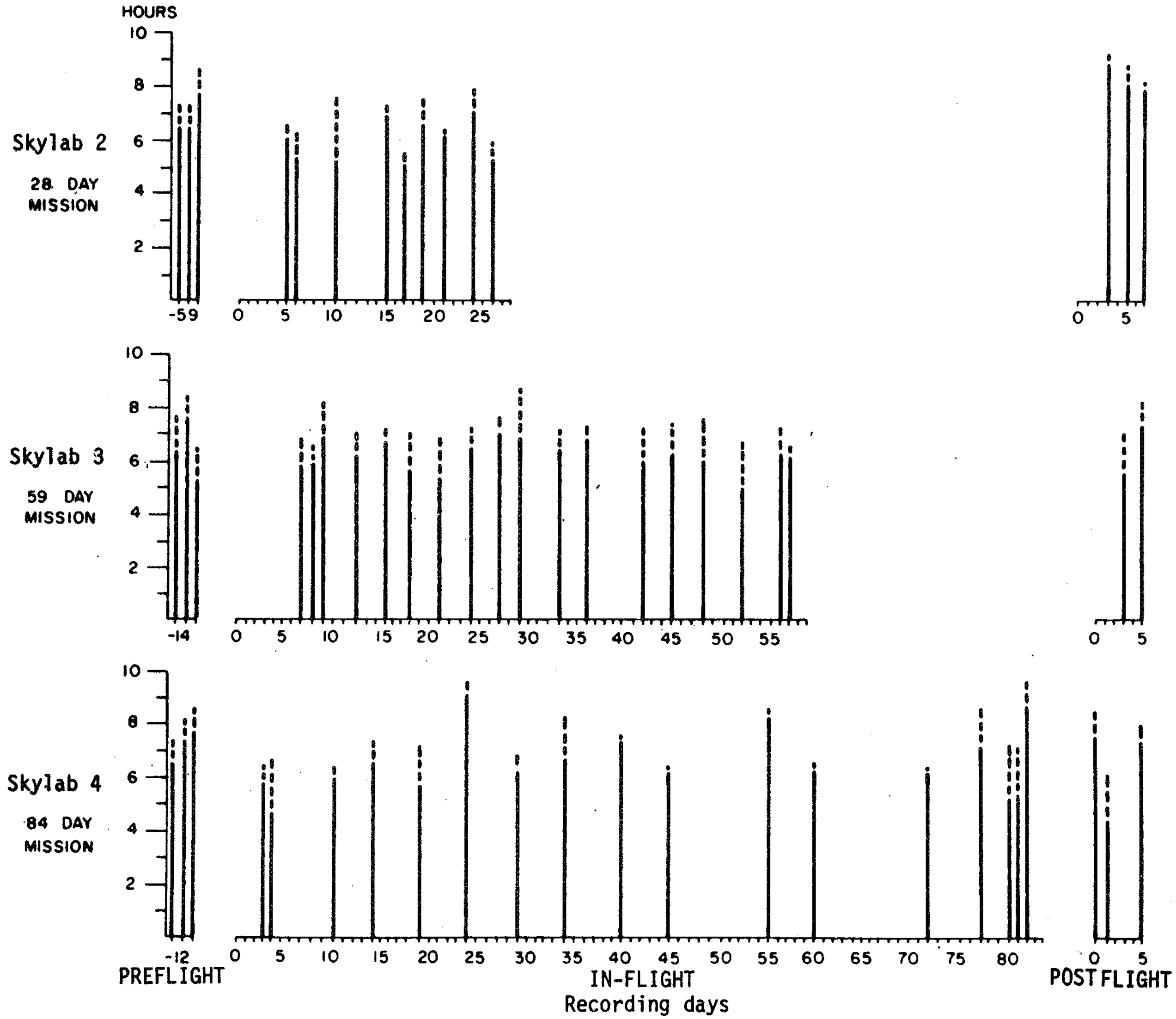

Figure 8. Total sleep time, all three Skylab missions.

preflight series, and the subject obtained in excess of 5 hours' sleep on all other nights. The in-flight average value of 6.3 hours (table II) is nearly the same as the preflight average (6.4 hours) and slightly lower than the postflight results (average, 6.6 hours).

A wide range of variation in the total rest and total sleep times was seen during the 84-day mission (fig. 8 part C). Total rest time ranged from a minimum of 6.4 hours on day 10 to a maximum of 9.8 hours on days 24 and 82. This parameter averaged 8.06 hours preflight, dropped by 30 minutes to 7.56 hours in-flight, and then rose to 7.67 hours postflight; but these variations were not statistically significant. Although most of the in-flight period was marked by considerable variation from one recording session to the next, there was a consistently lowered total rest time during the observations of the first 19 days. The five values of this period averaged 6.86 hours, or 1.2 hours below the preflight average.

Total sleep time tended to parallel total rest time, and thus long periods of time spent awake during the night were, in this mission as in the others, rare. Sleep time ranged from a low of 4.88 hours on day 4 to a high of 9.37 hours on day 24. The in-flight average value of 6.69 hours is about 36 minutes below the preflight average of 7.29 hours, but it is approximately 10 minutes higher than the postflight result of 6.53 hours. As in the case of total rest time, although the overall averages were not significantly altered, total sleep time was considerably lower during the first 19-day period. During this time, the average value was 5.87 hours, or 1.42 hours below the preflight average.

It is of interest that, while the initial 19-day period was characterized by a reduced time in bed and correspondingly reduced total rest time, it was also marked by a higher value for total awake time (0.99 hours average) compared to either the preflight average (0.77 hours) or the overall in-flight average (0.87 hours).

Sleep-Stage Characteristics

Sleep-stage characteristics for the three missions (expressed as percentages of the total sleep time for each recording night) are illustrated in figures 9, 10, and 11. Average percent figures for the various stages in the preflight, in-flight, and postflight periods are listed in tables I, II, and III. Comparisons of individual stage characteristics for the three missions are illustrated in figures 12 through 16.

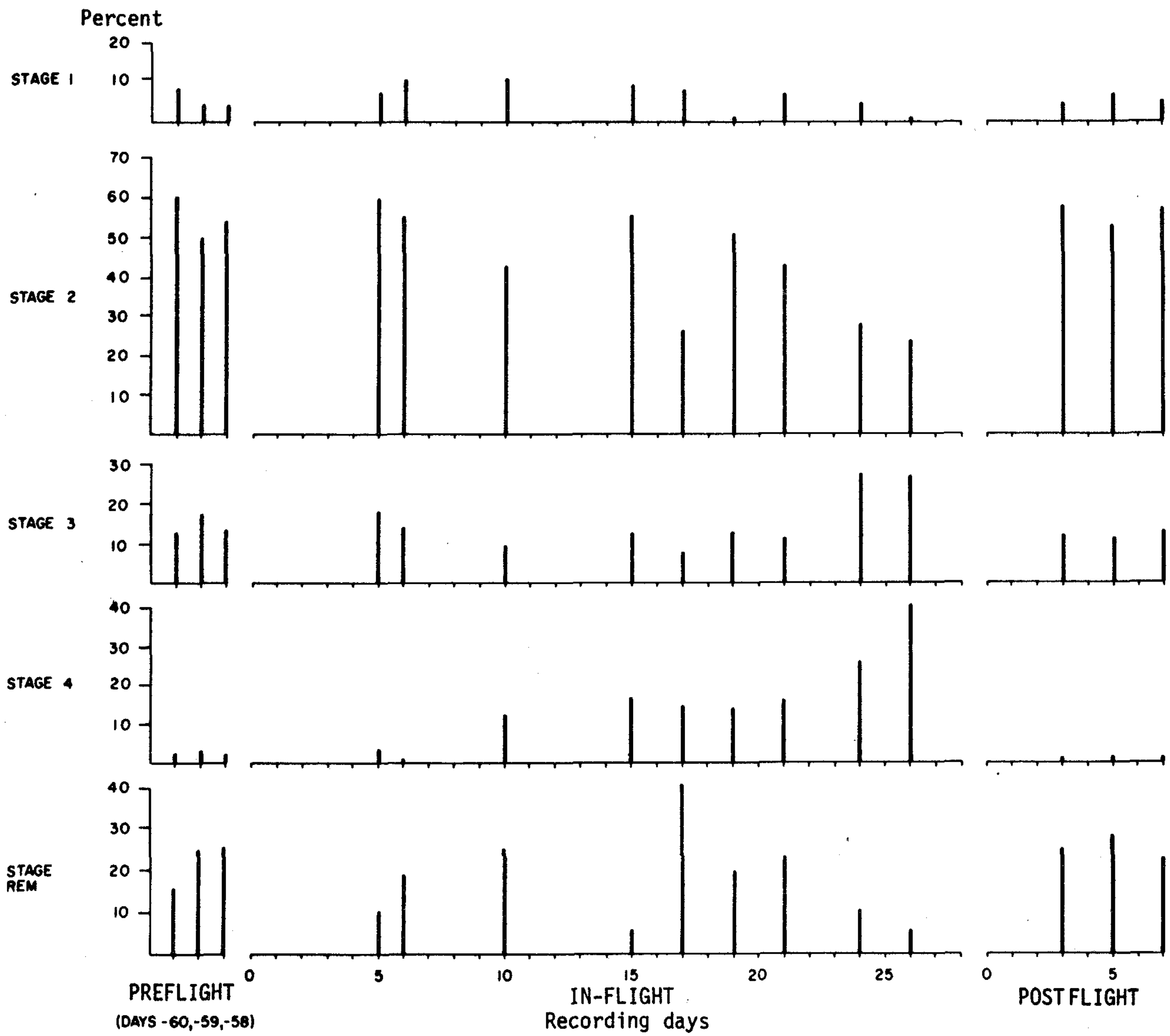

Figure 9. Sleep-stage percentages, 28-day mission.

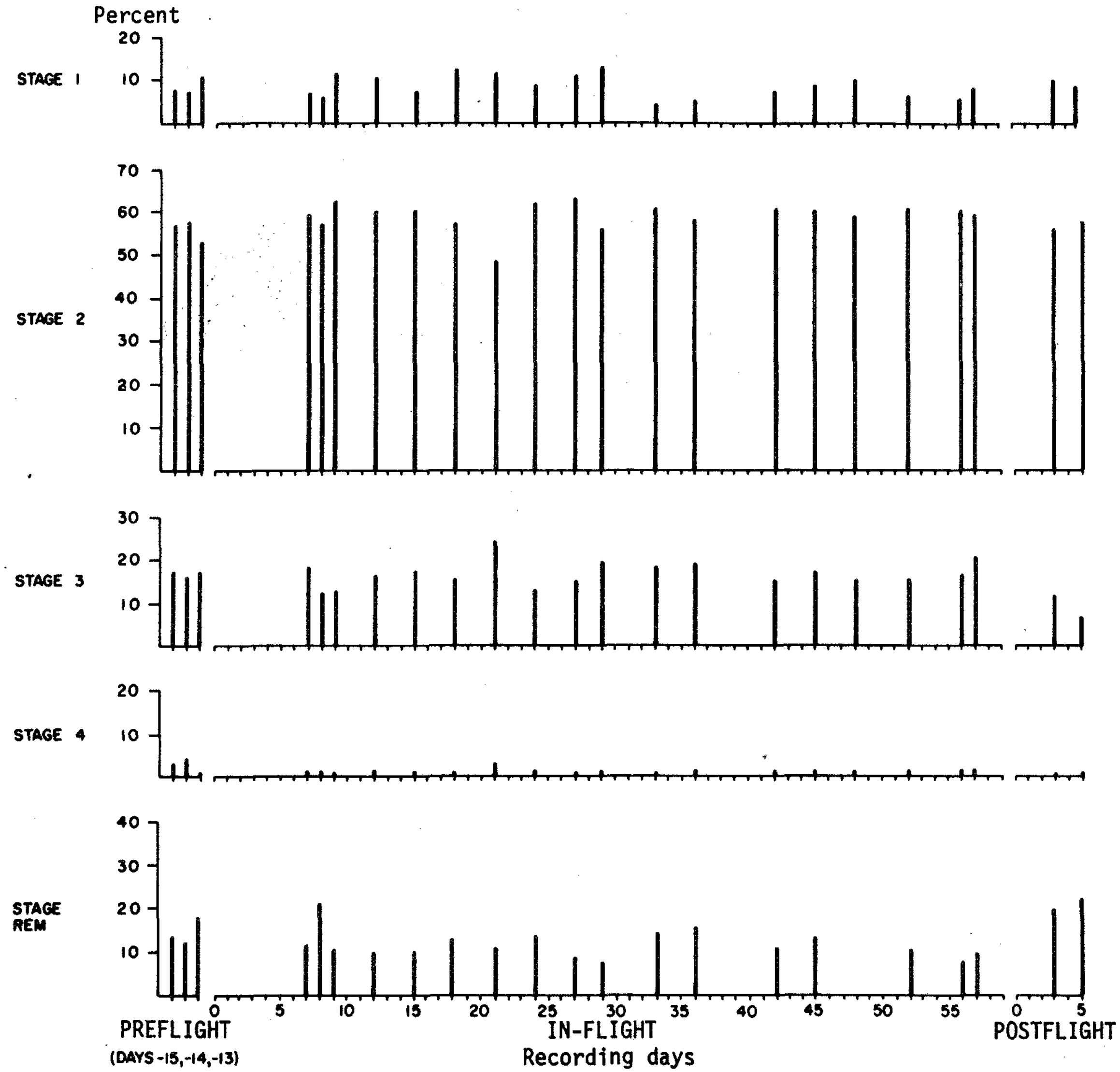

Figure 10. Sleep-stage percentages, 59-day mission.

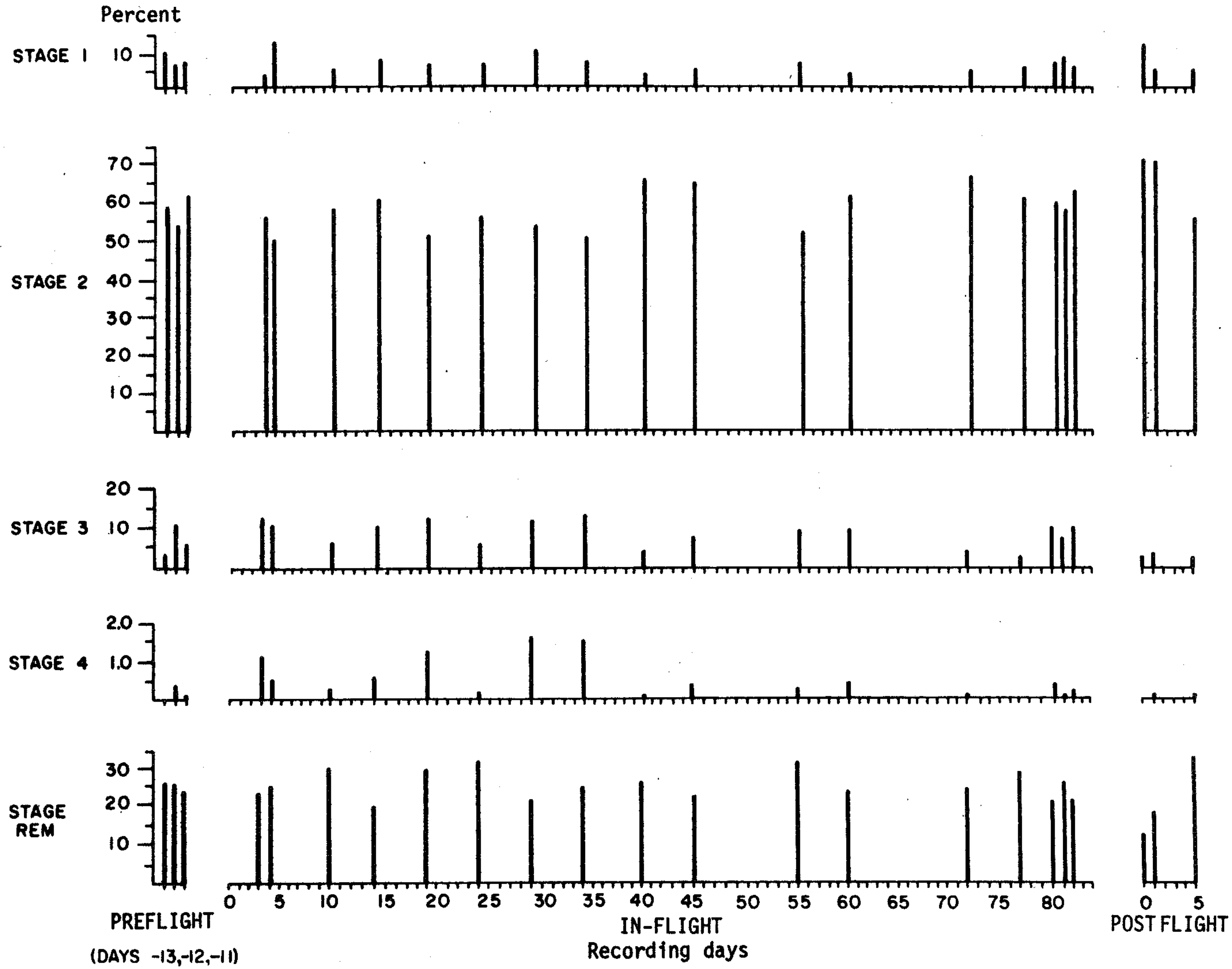

Figure 11. Sleep-stage percentages, 84-day mission.

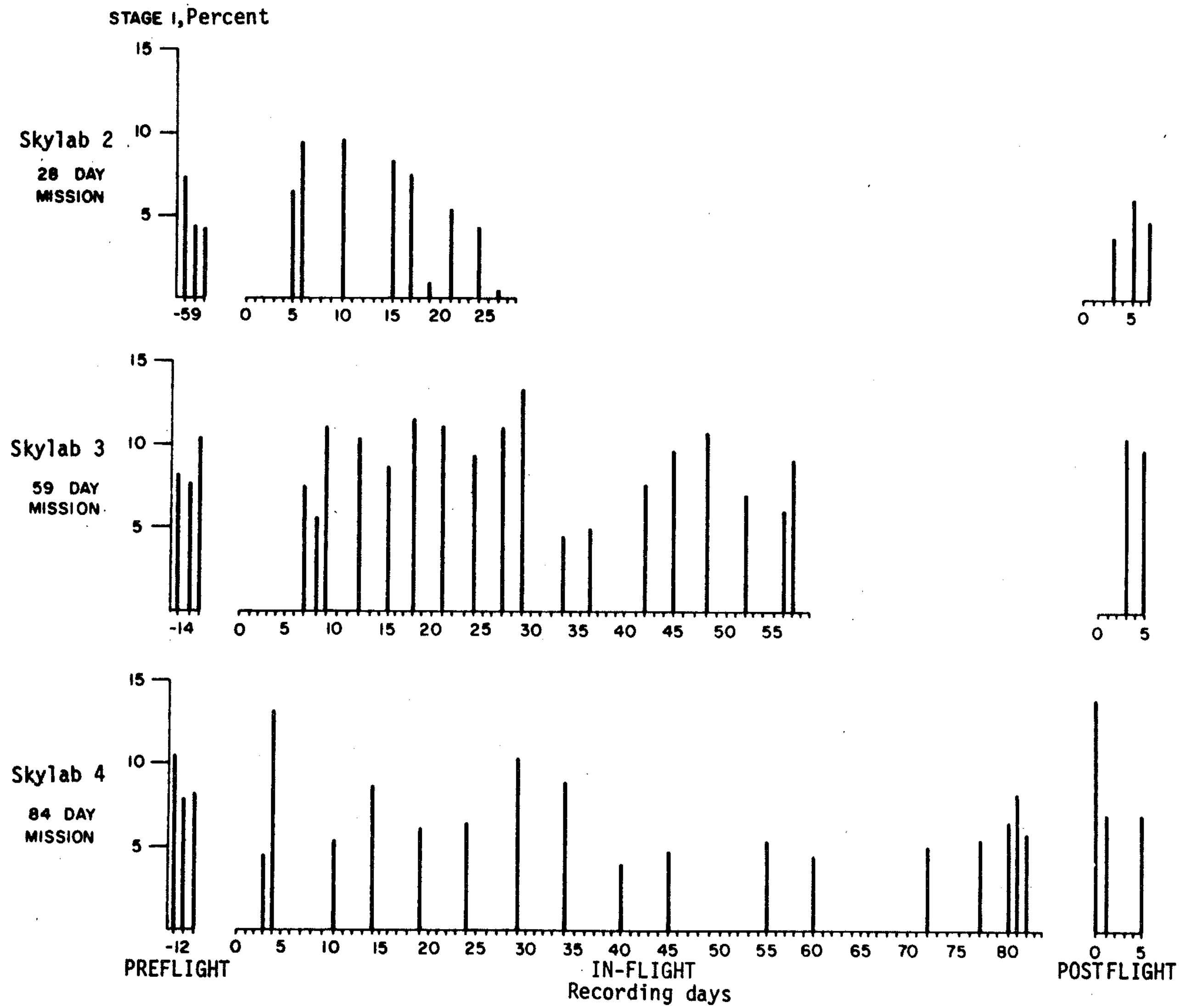

Figure 12. Percent Stage 1 sleep, all three Skylab missions.

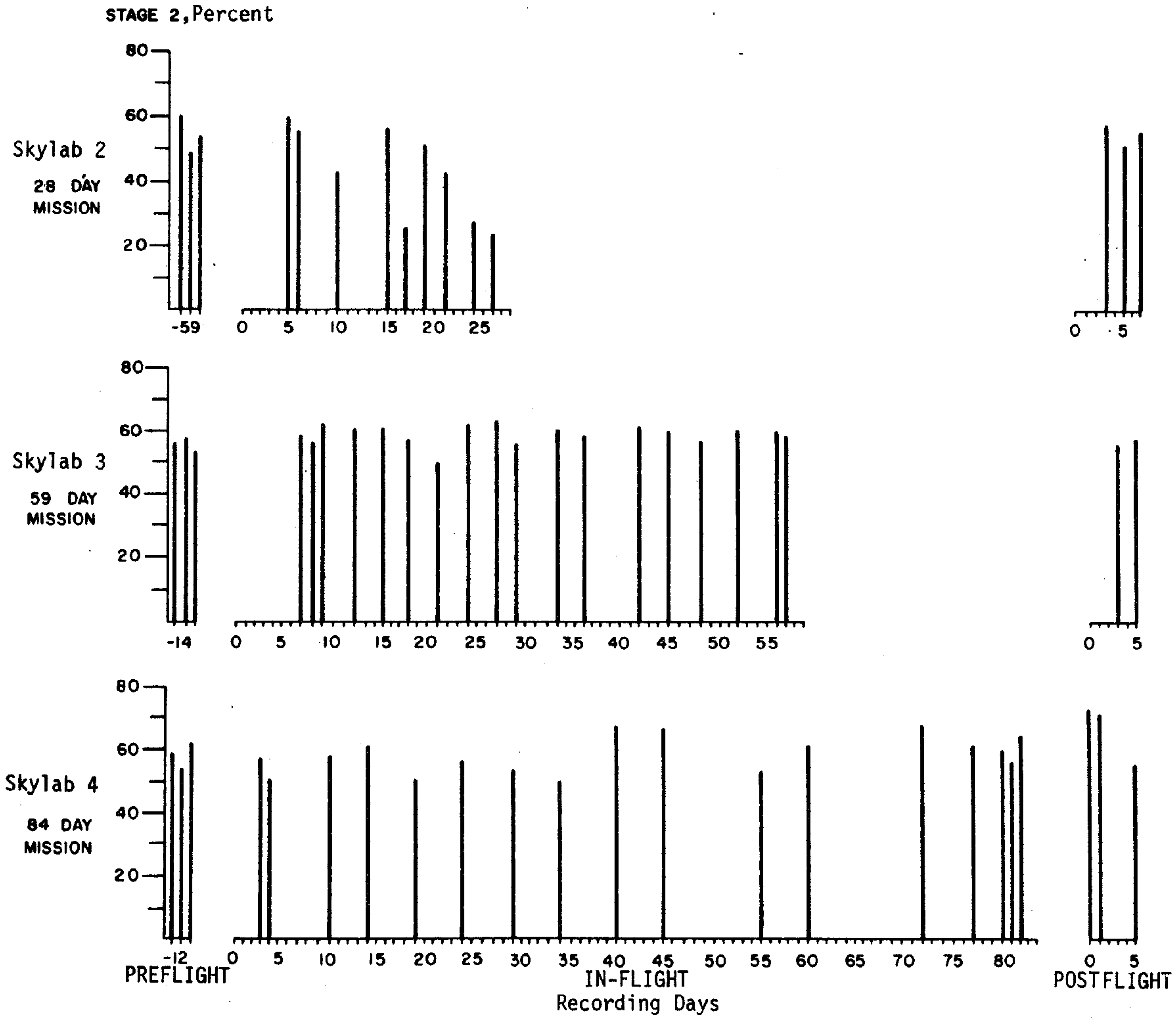

Figure 13. Percent Stage 2 sleep, all three Skylab missions.

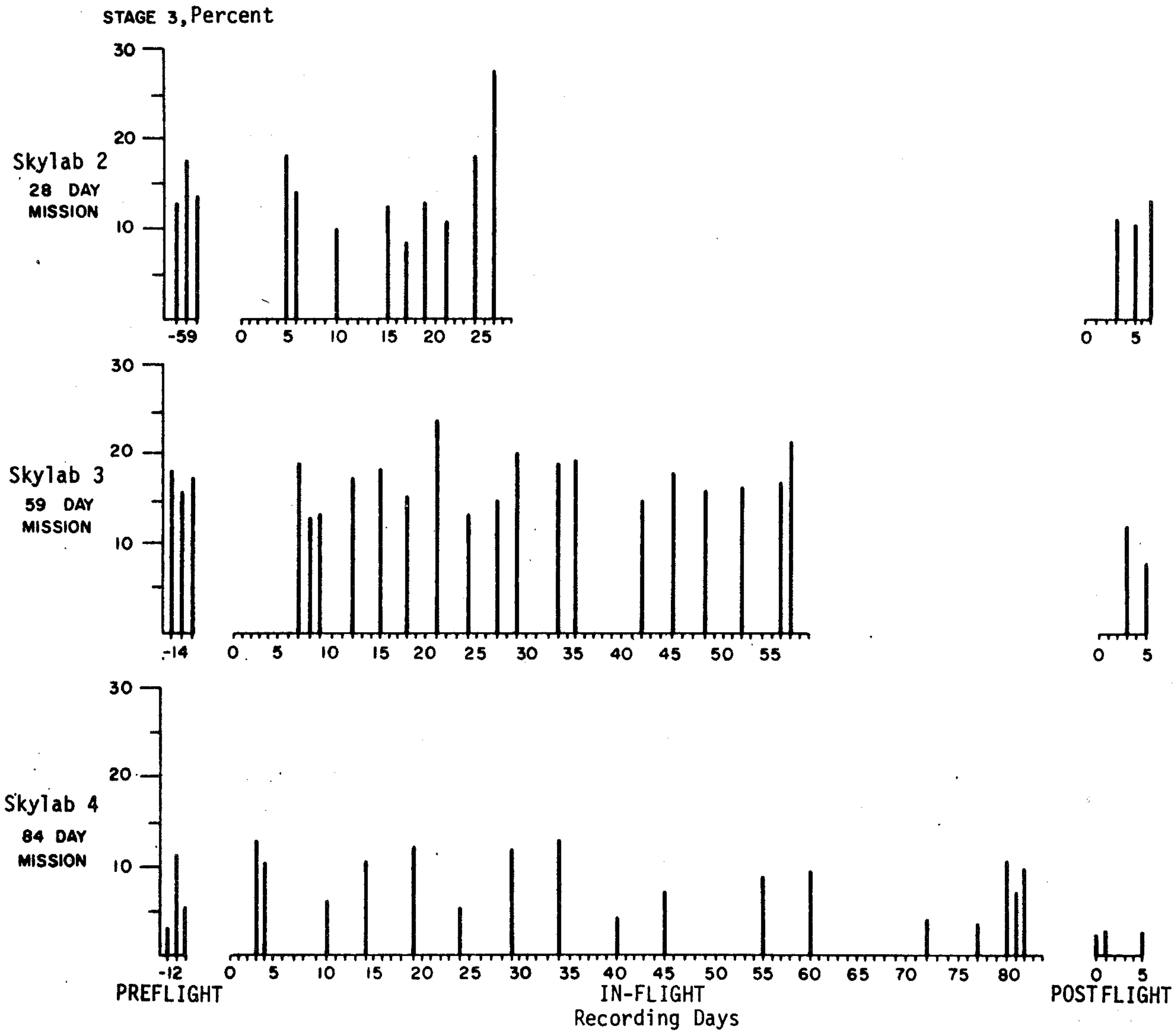

Figure 14. Percent Stage 3 sleep, all three Skylab missions.

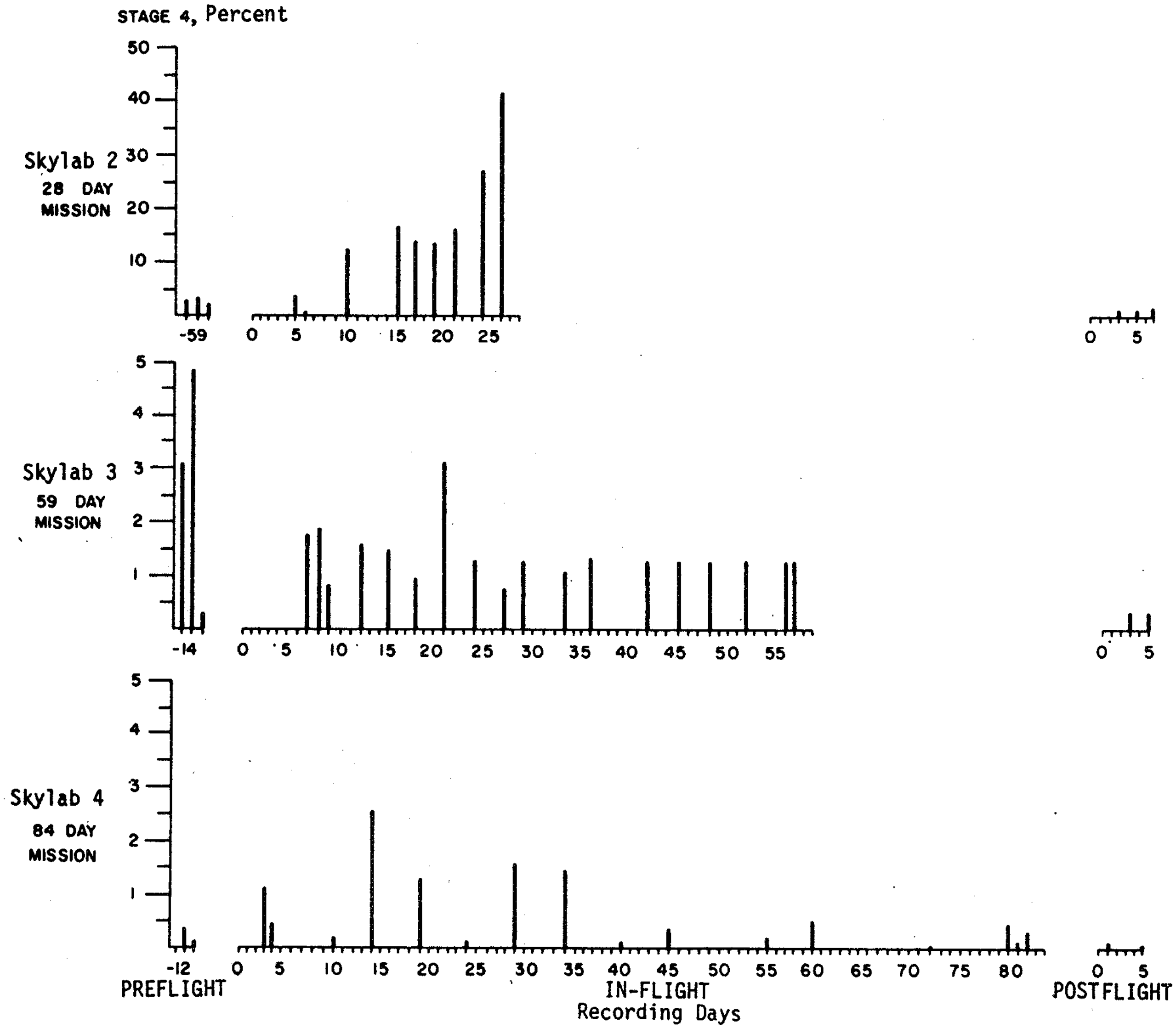

Figure 15. Percent Stage 4 sleep, all three Skylab missions.

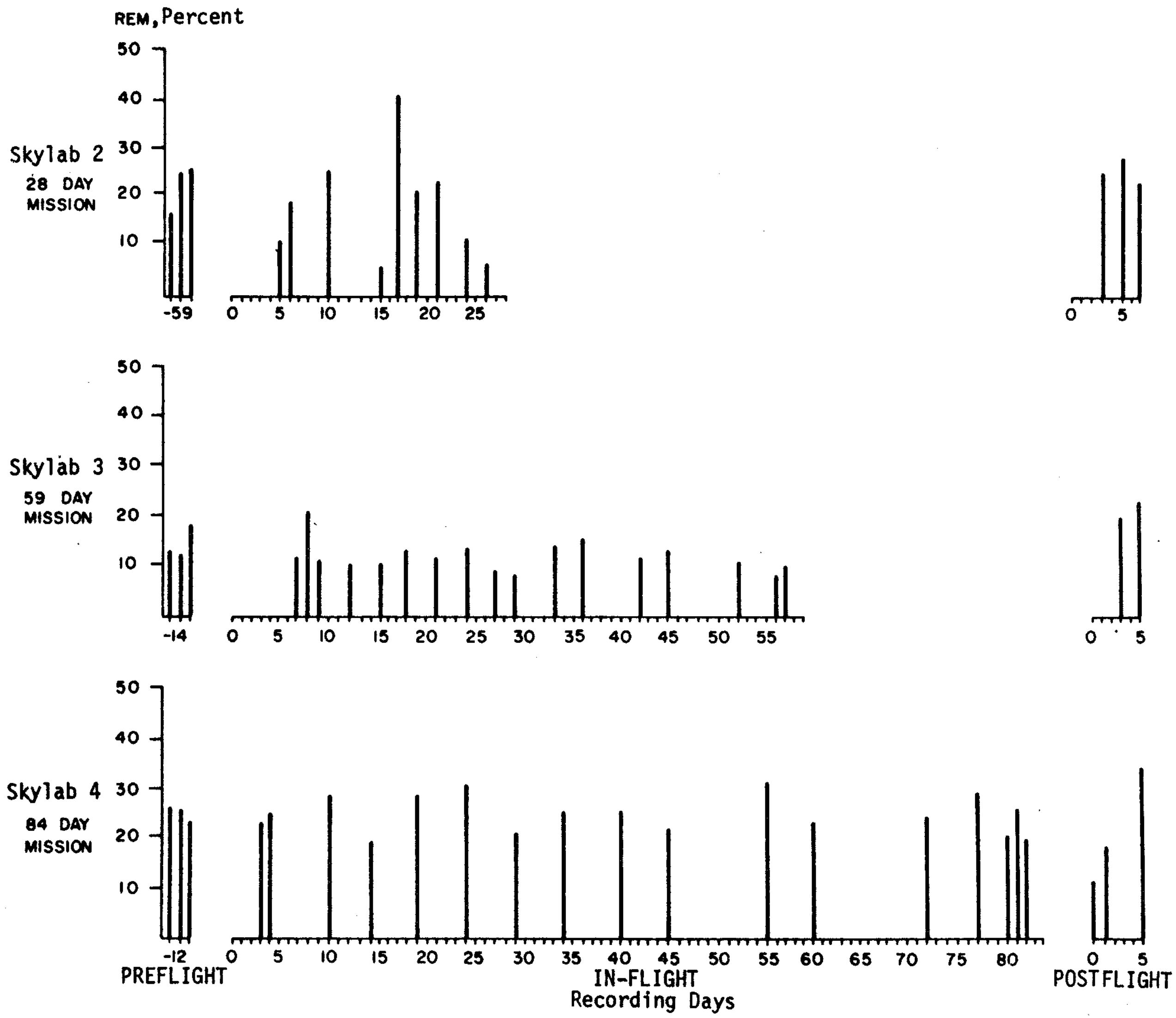

Figure 16. Percent REM sleep, all three Skylab missions.

If the average values are considered, stages 1, 2, 3, and REM were not significantly altered during the in-flight period of the 28-day mission (fig. 9). Stage 1 occupied 5.3 percent of the total sleep time preflight and averaged 6.0 percent in-flight and 5.1 percent postflight.. The day-to-day in-flight characteristics show a considerable fluctuation in stage 1 percent, with a tendency toward slightly decreased values in the latter portions of the flight (days 19 through 26).

Stage 3, averaging 14.8 percent in the preflight period, rose slightly to an average of 16.0 percent in-flight and dropped to 12.2 percent postflight. As seen in figure 9, a small increase in the stage 3 percent average was largely a result of moderate increases in this stage on days 24 and 26 at the end of the mission. Stage REM decreased only slightly from a 22.2 percent preflight average to 17.9 percent in-flight, although again there was considerable variation throughout the flight, with some tendency toward a more marked decrease near the end of the mission. The postflight stage REM average (25.0 percent) was somewhat higher than either the preflight or in-flight values, but it did not attain statistical significance.

Fairly clear-cut changes were seen in stage 2 and stage 4 percentages. In both cases, the most obvious alterations were seen in the last few days of the flight. Stage 2 dropped from an average of 54.8 percent preflight to 43.4 percent in-flight, returning to 56.6 percent postflight. These differences, however, were not statistically significant. Similarly, stage 4 rose from 2.9 percent preflight to 16.7 percent in-flight, then dropped significantly ($P < 0.05$) postflight to 1.1 percent.

Thus, the 28-day mission was characterized by increased percentages of stages 3 and 4 and corresponding decreases of stages REM, 1, and 2, with the alterations confined primarily to the last few days of the flight.

Sleep-stage features for the 59-day mission are illustrated in figure 10, and average values are tabulated in table II. Stage 1, averaging 8.8 percent preflight, showed considerable variation in-flight but averaged almost the same (8.9 percent). The postflight average value of 10.2 percent was only slightly above the in-flight result. Stage 2 remained fairly consistent throughout (preflight, 56.3 percent; in-flight, 59.7 percent; postflight, 57.8 percent), although there was a decrease during the final days of the flight (days 56 and 57). Thus, neither stage 1 nor stage 2 changed significantly. Stage 3 was similar in-flight (17.5 percent) and preflight (17.4 percent) and also exhibited a change near the termination of the flight, tending to increase slightly. The postflight average of 10.1 percent, however, was significantly lower ($P < 0.01$) than either the preflight or

in-flight values. This subject showed very little stage 4 sleep in his preflight study (2.8 percent), and this parameter decreased significantly ($P < 0.05$) in-flight (1.4 percent) and postflight (0.4 percent) ($P < 0.05$). Stage REM showed the greatest alteration, dropping from 14.7 percent during the preflight baseline series to 12.1 percent in-flight and then rising significantly ($P < 0.01$) to 21.6 percent postflight. This postflight increase in REM was also significantly greater than the preflight value ($P < 0.05$). The REM decrease seen in-flight was most prominent in the final phase of the study (days 52, 56, and 57).

Sleep-stage characteristics for the 84-day flight are summarized in figure 11, and the average values are tabulated in table III. Stage 1, averaging 8.9 percent preflight, dropped in-flight to 6.8 percent, then rose postflight to 9.4 percent, a value slightly higher than the preflight average. There were no clear-cut trends discernible over the in-flight course of the mission. The stage 2 values were relatively consistent during the in-flight period, and the average value of 58.5 percent was identical to the preflight average. Postflight stage 2 showed a small increase, averaging 66.1 percent for the three days. As indicated in figure 11, the first two postflight days were significantly higher than any of the preflight or in-flight values. Stage 3 was not significantly different in-flight (8.8 percent) as compared to the preflight value (7.1 percent). Postflight, however, this parameter fell to an average of 2.7 percent with all three values falling well below the preflight and in-flight averages ($P < 0.01$). This subject showed very little stage 4 preflight, averaging only 0.2 percent, and maintained a low level throughout the flight, with the in-flight average at 0.5 percent. There was a further reduction postflight, with the average value less than 0.1 percent. Stage REM percent averaged 25.3 percent preflight, and the in-flight average remained at 25.3 percent. There was considerable variation in this parameter over the course of the mission, however, but no definite trends were observed. Although the postflight average of 21.8 percent was slightly lower than either the preflight or in-flight average value, it is obvious (fig. 11) that this parameter was not stable in the postflight period. The value of 12.1 percent on the first postflight night is substantially lower than any of the preflight or in-flight values for this characteristic. On the other hand, the value of 34.6 percent seen on the sixth postflight night is considerably higher than any of the values seen preflight or in-flight.

REM Latency

REM latency is defined as the elapsed time from sleep onset (*i.e.*, the first appearance of stage 2 sleep) until the onset of the first stage REM period of the night. Because of the relative unreliability of this

measurement when derived from the results of automatic analysis, only the values obtained from visual analysis have been reported below. Compared to preflight values, this measure was shortened during the postflight period of the 28- and 59-day missions. During the 28-day mission (fig. 17 part A), the REM latency averaged 1.5 hours preflight and 1.1 hours postflight, or a decrease of 24 minutes. Although substantial, this decrease was not statistically significant. The phenomenon was more apparent during the 59-day mission, as illustrated in figure 17 part B. In the preflight baseline period, the values ranged from 1.6 to 2.2 hours, with an average latency of 1.9 hours. The in-flight values showed considerable fluctuation, but the average of 2.1 hours was not significantly different compared to the preflight results. In the postflight period, however, the latency dropped to 0.9 hours, which represented a decrease of 1 hour below the preflight findings. This postflight REM latency was significantly ($P < 0.01$) less than both preflight and in-flight values.

REM latencies during the 84-day mission (fig. 17 part C) showed little change in the in-flight period compared to either preflight or postflight studies. The in-flight average value of 1.31 hours is not significantly different from the 1.47 hours figure seen preflight, while the value of 1.46 hours seen postflight is almost identical to the preflight result. It is worthy of note that the first postflight night exhibited a relatively long REM latency, while the second and third postflight nights were marked by much shorter periods.

Number of Awakenings

The number of awakenings per night was calculated for the data based upon human visual analysis only, and this information is presented comparatively in figure 18.

The 28-day flight was characterized in the preflight period by an average of 19.7 awakenings per night, with a range of 16 to 24. Postflight, the average was 22, with a range of 20 to 26. Although only two in-flight nights are available for comparison, in both instances the number of awakenings was below the preflight and postflight levels.

The number of awakenings during the preflight baseline series for the 59-day mission ranged from 34 to 51, with an average of 40.7. In-flight, a greater range was seen, extending from a low of eight on day 33 to a high of 70 on day 9, with an average of 39.3. Postflight, the average number of awakenings dropped to 28.5, with a range of 26 to 31. The number of arousals seen during the in-flight portion of this mission peaked at day 9 and showed a tendency to decline toward baseline or sub-baseline levels as the flight progressed.

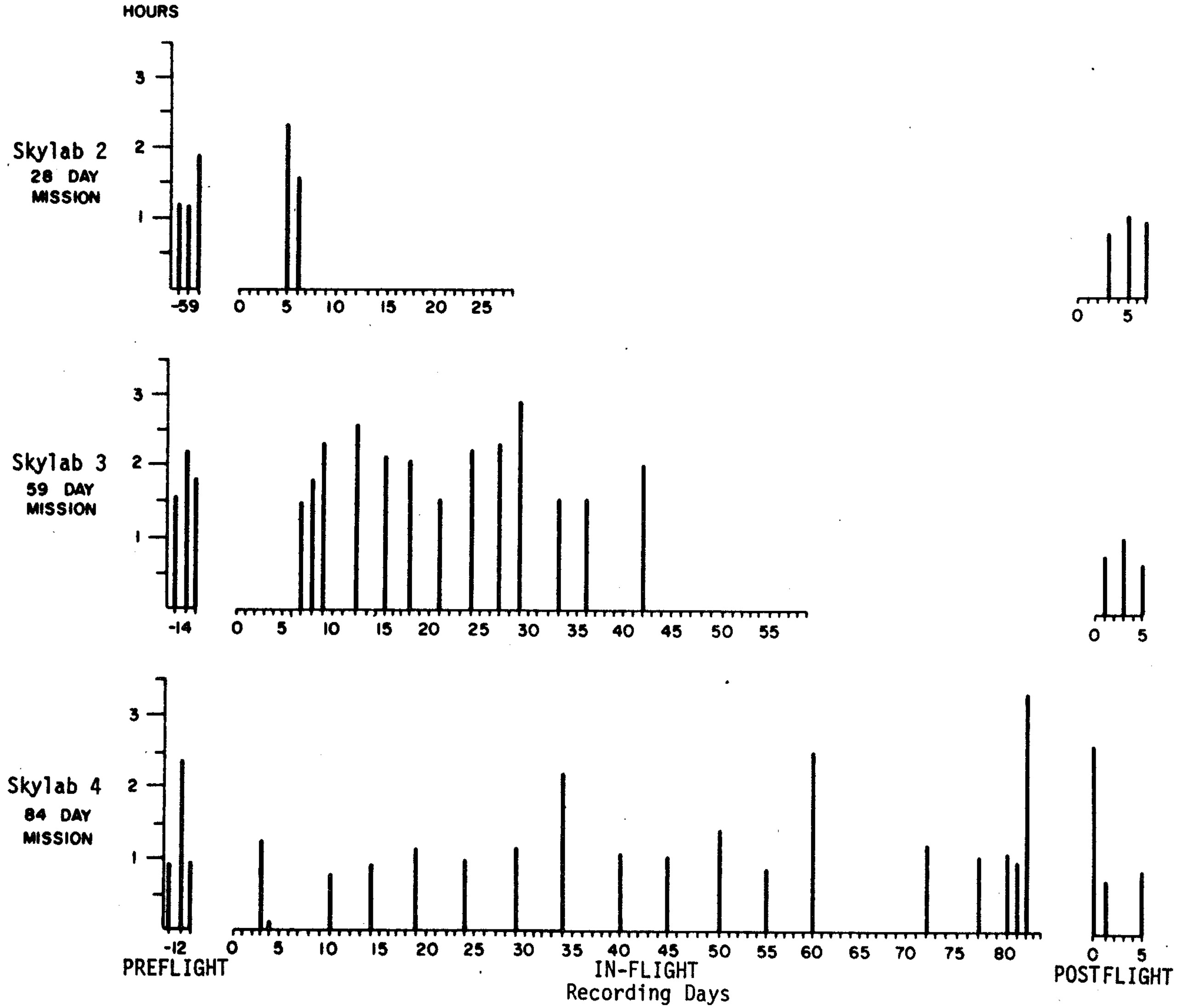

Figure 17. REM latency, all three Skylab missions.

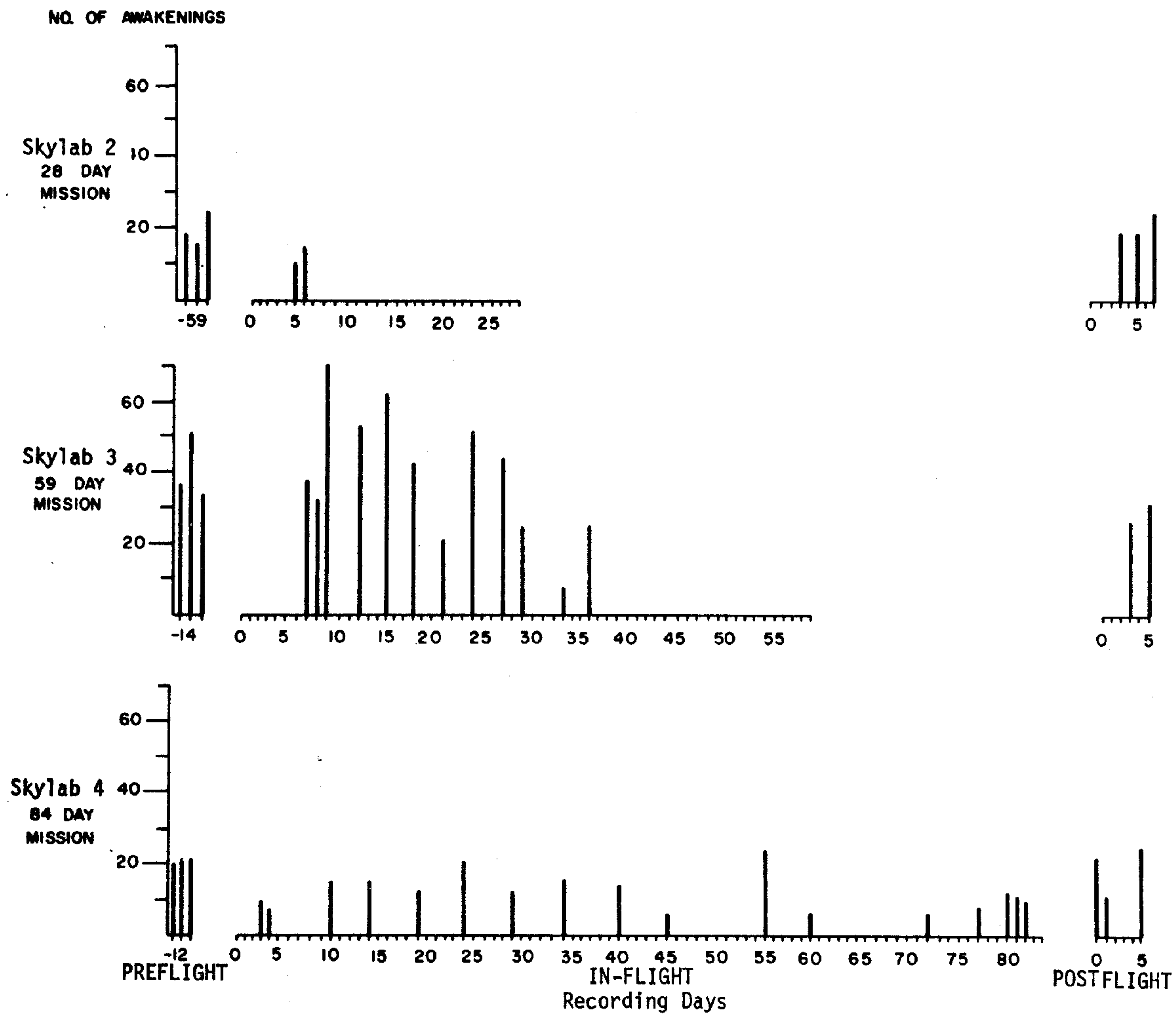

Figure 18. Number of awakenings, all three Skylab missions.

In the 84-day mission, the number of awakenings declined from a preflight average of 20.7 (20 to 21) to an in-flight average value of 12, with a range of 6 to 22 ($P < 0.01$). Postflight, the level rose to an average of 18.7, with a range of 11 to 24 ($P < 0.05$). Although the in-flight period was characterized by a good deal of variation in this measure, there was no consistent trend noticeable.

DISCUSSION

Overview

Sleep Latency. The three Skylab flights differed with respect to sleep-latency characteristics. No significant changes in this parameter were noted during the 59-day mission. In the 28-day mission, the in-flight and postflight latencies were significantly lower than the preflight values. The 84-day flight was characterized by relatively long sleep latencies in the early portion, with the return to values typical of the preflight and postflight periods in the latter half of the mission.

The alterations seen during the 28-day mission are apparently explainable, at least in part, by a difference in the subject's routine rather than by a direct influence of the environment. This individual typically spent a few minutes reading in bed prior to falling asleep during preflight studies in his own home. However, he did not continue this practice either during the flight or in the postflight period.

In only the initial portion of the 84-day mission was a degradation in sleep latency seen. As illustrated in figure 7, even in this case the magnitude of the alterations seen was not great, and on only two nights were the values outside the range seen during the preflight studies. In addition, it is significant that these alterations occurred in the early portion of the study and thus cannot be attributed to the longer duration of this mission. Consequently, it appears reasonable to conclude that space flight and the associated weightless condition do not significantly interfere with the process of falling asleep, although in some individuals there may be an adaptive period during which some difficulty is experienced.

Sleep Time. The greatest overall change in total sleep time occurred during the 28-day mission, when a decrease of approximately one hour was seen in-flight compared to preflight. As indicated previously, this was a voluntary reduction in sleep time by the subject himself and thus cannot be considered as insomnia. The subject did not complain of sleep loss and apparently was sleeping as much as he actually required. No significant changes in sleep times were noted during the

59- or 84-day missions. If the initial portion of the 84-day flight is considered separately, however, it is evident that the subject experienced some difficulty in sleeping in this time. Sleep was also more of a problem subjectively to this individual, and he indicated on several occasions that his sleep was not adequate. Sleeping medication was occasionally used by the subject, although not on the nights which were monitored.

Of the three subjects, then, only the one studied during the 84-day flight experienced real difficulty in terms of total sleep time. In this case, the problem diminished with time, although sleeping medication was used sporadically throughout the flight. In terms of any possible adverse effect upon performance capability, it seems that only during the initial period of the 84-day mission would this have been likely to be caused by sleep loss. This cannot be precisely assessed because of the long sample intervals; however, even generalizing the worst case (4.9 hours on day 4), a severe influence upon performance would not be expected.

Stage Characteristics. Several changes in sleep-stage characteristics were common to all three flights. Stage 3 (fig. 12), which was significantly elevated during the in-flight portion of the 28-day mission, also rose in-flight in the 59- and 84-day missions. Postflight, the stage 3 (fig. 14) and stage 4 (fig. 15) values were below the preflight average in all three flights. A consistent elevation of stage REM (fig. 16) was seen in the late postflight period of all flights and was accompanied by a shortening of REM latency.

Number of Awakenings. Although this measure was highly variable, in general the in-flight period of all missions was characterized by no overall increase in number of arousals, and in the case of the 84-day mission, there were significantly fewer awakenings.

Significance of Results. The results obtained during the three Skylab missions suggest that prolonged space flight, with its accompanying weightless state, is not directly associated with major adverse changes in sleep characteristics. The alterations in sleep patterns that were observed were not of sufficient magnitude to result in significant degradation of performance capability. These conclusions were somewhat unsuspected, since previous studies of confinement, social isolation, and unusual environments involving polar explorers (12-15), underwater habitats (16), long-duration flight operations (17), and astronauts (1) have all reported sleep loss and/or disturbances of sleep.

Early in the manned space flight program, speculation arose that the zero-g state might, itself, in some way disrupt the normal sleep/wakefulness mechanisms. It had been suspected that the altered sensory input to the central nervous system associated with weightlessness might interfere with sleep onset and result in prolongation of sleep latency and lead to long periods of wakefulness following arousals from sleep. The Skylab results, however, show that in none of the missions was sleep latency a significant problem over the course of the flight, and in only one case, that of the 84-day flight, was it even a temporary difficulty. Furthermore, there was no evidence of consistently increased amounts of time spent awake during the night; in fact, the number of awakenings tended to decrease in-flight. The results indicate that during space flights of long duration, it is possible to obtain adequate amounts of sleep during regularly scheduled eight-hour rest periods.

The most consistent and most significant changes were actually observed in the postflight period of all flights and pertained to sleep-stage characteristics. Thus, stages 3 and 4 tended to be decreased in the postflight period as compared to both preflight and in-flight results, while stage REM was elevated in the late postflight period (after day three following recovery) and was accompanied by a shortening of REM latency.

The postflight changes in stage REM are worthy of further consideration. Since such findings are typical of the rebound effect seen following periods of relative deprivation of stage REM (18), the question of a significant deprivation in-flight arises. This question is, however, somewhat difficult to accurately assess. When the overall averages are considered, there appears to be no significant decrease in REM in-flight. However, when the individual data points are considered (fig. 16), there is a suggestion that perhaps REM percent did decline in the terminal portion of the flights. This tendency is most prominent in the case of the 28-day mission, where a relatively steady decline in stage REM percent is evident after day 17. Such a trend is less obvious in the case of the 59-day mission, although the last two days are below the preflight average value. In the case of the 84-day flight, the latter portion of the mission shows only a slight indication of a decrease in stage REM. Even though the results appear to argue against a prior period of REM deprivation in-flight as a contributing factor, it must be emphasized that recordings were not made during the last two nights of each mission, and consequently this situation cannot be fully assessed.

A shortening of REM latency was observed in the late postflight period of all missions and accompanied the increase in REM percent noted during that time. This phenomenon has also been reported as a manifestation of a prior period of REM deprivation. Arguing against REM deprivation as a causative agent of this change is that no lessening of the effect was evident even on the sixth night following recovery of the 59- and 84-day missions nor after the eighth night following the 28-day mission. Similarly, it seems unlikely that the changes in stage REM can be attributed to alterations in the astronauts' sleep schedules (*i.e.*, the advances in bedtime near the termination of each mission). It has been reported that delaying sleep periods by four hours results in a shortening of REM latency, but such findings have not been reported with comparable advances in sleep onset. Furthermore, while delaying sleep periods has been found to increase REM percent, advancing sleep periods resulted in a decrease in REM percent (19).

Postflight data from the 84-day mission further suggests that the increase in REM percent seen late postflight is actually a delayed phenomenon and follows a period of relative REM suppression in the immediate recovery period. In fact, the REM percent value of 12.1 percent on the first night following recovery is well below any REM percent value seen either preflight or in-flight. The value seen on day five after recovery, in the late postflight period, is correspondingly well above any value seen either preflight or in-flight. Delayed REM rebound is not a typical finding in experimental situations involving REM deprivation. It has been reported following periods of total sleep deprivation, in which case there is an elevation of stages 3 and 4 in the first recovery night and a later elevation of stage REM (20). However, in none of the three Skylab flights was a postflight elevation of stages 3 and 4 noted, and in fact these paramters tended to decline. Consequently, in these cases a delayed REM rebound appears to argue against prior sleep deprivation as the cause of the postflight REM changes.

In view of these findings, it seems plausible that the decreased REM latency and increased REM percent represent a true influence of the reinstated one-g condition and that this signifies a basic alteration in the sleep/wakefulness mechanism of the central nervous system.

It has been postulated that sleep, and in particular the REM stage, may be of importance in the organization and maintenance of memory (21-23). According to this view, REM may be involved in consolidation or reprograming of short-term memory into a more permanent or long-term form. If this hypothesis is correct, then it might be predicted that tasks associated with acquisition of new motor skills and coordinated motor activity might be associated with an increased need for stage REM sleep.

In support of this hypothesis, it has been found that during the period of adaptation to an inverted visual field, REM time was increased (24, 25). After declining to relatively normal levels after adaptation, reverting the visual field to normal was again accompanied by an increase in REM-sleep amount. The situation in space flight may be analogous, since the withdrawal of gravitational cues and the decrease in proprioceptive input and altered vestibular input place a considerable burden upon the visual system as the sole means of maintaining spatial orientation. Following the mission, the return to Earth similarly requires a period of adaptation to the one-g condition. It might be speculated, then, that the increase in REM time seen postflight was a manifestation of this hypothesized mechanism. There is no evidence in the Skylab data that adaptation to zero-g is accompanied by an increase in REM time; in fact, the in-flight values were either the same or lower than preflight values. The hypothesis cannot, however, be adequately evaluated, since no sleep data was obtained prior to day 3 in any of the flights; thus, pertinent changes could conceivably have been missed. If such in-flight changes were present, however, they evidently were of shorter duration than those seen postflight, where changes were seen until the eighth day after recovery.

CONCLUSIONS

The objective results of these sleep monitoring experiments indicate that man is able to obtain at least adequate sleep over prolonged periods of time in space and during regularly scheduled eight-hour sleep periods. The alterations in sleep patterns which were observed during these missions were not of the type, nor of sufficient magnitude (with the possible exception of the initial portion of the 84-day mission), to result in significant degradation of performance capability. The most notable changes seen actually occurred in the postflight period, and this suggests that perhaps the readaptation to one-g is somewhat more disruptive to sleep than the adaptation to zero-g. Yet, even in this case, the alterations seen were those of sleep quality and not quantity. It is also worthy of emphasis, particularly with respect to the results seen during prior space flights, that none of the Skylab crewmen complained excessively of sleeping difficulties. In fact, most reported no problems with respect to sleep, and some expressed the opinion that sleep was perhaps better in space. Viewed overall, these results are somewhat surprising because of the frequent complaints of insomnia during pre-Skylab missions. Apparently, the problems encountered during earlier space flights were not simply due to the imposed zero-g environment. The Skylab orbiting laboratory differed considerably from spacecraft of the Apollo and Gemini types, although the gravitational and atmospheric factors were the same in all cases. The working volume of the spacecraft is most likely the

influential factor in terms of sleep. Skylab provided adequate room for separate eating, exercising, working, and sleeping areas within 12 763 cubic feet of living area. The Apollo spacecraft measured only approximately three percent of this volume, while the Gemini craft contained less than one percent. In these smaller spacecraft, all daily tasks were more difficult, and the astronauts undoubtedly had a greater sense of confinement. In addition, Skylab allowed the establishment of a daily routine which was, in most respects, directly comparable to ground-based, everyday activity. The crewmen maintained their Houston-based time reference throughout the flights and, for the most part, worked during conventional hours. The individual sleeping compartments were a definite improvement over the prior spacecraft systems, and this undoubtedly greatly minimized or eliminated interference with sleep caused by activity of other crewmen. In general, the element of risk or danger present in all space flights seemed to be minimized in Skylab by the presence of an established daily routine, and this also may have contributed to the improvement in sleeping conditions.

The results also suggest areas for future study with respect to the acquisition of scientific data and in terms of man's overall adaptation to life in space. As indicated previously, the changes in sleep-stage characteristics seen postflight possibly do represent a direct influence of the altered gravitational factors upon the sleep/wakefulness mechanisms. Future experiments, if properly designed, could provide information of basic importance to our understanding of sleep. In terms of human capabilities, we feel confident that flights of two to three months will not be jeopardized by sleeping difficulties, but beyond this point we must continue to carefully evaluate sleep and insure proper work-rest scheduling.

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VISUAL LIGHT FLASH OBSERVATIONS ON SKYLAB 4

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ABSTRACT

During the Skylab 4 mission, two separate light flash observation sessions were performed on mission days 74 and 81 by the pilot, William R. Pogue. These sessions occurred during orbits that allowed observations from high northern geomagnetic latitudes, through the equatorial region, and on to southern geomagnetic latitudes. The South Atlantic Anomaly was also traversed during each session. During each session, the Pilot (in the sleep-restraint mode) donned a blindfold and recorded his observations of flashes on the voice recorder.

The data obtained indicate a latitude effect on the frequency of the flashes; this effect would be expected if primary cosmic particles cause the flashes. Additionally, high flash rates (15 to 20 flashes/min) were observed when the spacecraft was over the center of the South Atlantic Anomaly. This observation has stimulated questions regarding the possible presence of trapped particles (larger than protons) in the South Atlantic Anomaly. Further observations and measurements regarding light flashes are planned for the Apollo-Soyuz Test Project.

INTRODUCTION

The observation of light flashes was first reported by the Apollo 11 Lunar Module pilot, Edwin Aldrin, with subsequent observations made on all Apollo missions (1,2). Professor C. A. Tobias predicted as early as 1952 (3) that this type of visual phenomenon would be experienced by humans when exposed to heavily ionizing cosmic particles. Although it has been quite generally accepted that the light flashes observed were caused by passage of cosmic particles through the visual apparatus, the exact mechanism of particle interaction is still uncertain. Some investigations (4,5,1,6,7,10) support the premise that the visual flashes are caused by direct particle/retina interaction while others (8,9) tend to favor Cerenkov radiation from relatavistic particles as their

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etiology. While both mechanisms probably contribute, the current consensus seems to be that most of the flashes result from direct ionization energy loss as the particle traverses retinal cells. In either case, if cosmic particles are the cause, a strong latitude effect of the light flash rate would exist for an observer in earth orbit. This effect is a consequence of the geomagnetic cutoff and the steep energy spectrum of cosmic ray fluxes. In other words, near the equator only cosmic particles with very high energy can reach orbital altitudes, while near the magnetic poles particles of much lower energies can reach comparable altitudes.

The primary objective of the study reported here was to investigate the frequency and character of visual light flashes in near earth orbit as the Skylab trajectory passes from northern to southern latitudes. Because the trajectory periodically passed through the South Atlantic Anomaly, another study objective was the investigation of possible visual flashes during passage through this region.

PROCEDURE

Two periods of observation by the pilot were planned. These observation sessions were accomplished on orbits selected to provide data on both latitude and South Atlantic Anomaly effects. Unfortunately, no single orbit possessed ideal geomagnetic latitude and anomaly conditions. Hence the first session provided the best latitude conditions but passed only through the edge of the South Atlantic Anomaly region. The second session passed through the center of the South Atlantic Anomaly but did not achieve as high geomagnetic latitudes. The first observation session occurred on mission day 74 and was 70 minutes in duration, while the second occurred on mission day 81 and was 55 minutes long. The second period was shorter because of very critical time limitations during the last few days of the mission.

At the start of each session the Pilot got into his sleep restraint, set a timer for the prescribed period (either 70 or 55 minutes), donned a blindfold, and began observing for light flashes. Approximately the first 10 minutes of each session was allocated for dark adaptation by the subject. During the first session no particular position in the sleep restraint was specified. The Orbital Workshop was in a Solar Inertial Mode during both periods and local noon occurred very close to equator passage in both cases. For the second session, directions were given for head positioning which placed the anterior-posterior axis of head parallel to the Earth's magnetic field lines in the anomaly.

The occurrence of each light flash event along with its description was voice recorded on the onboard tape recorder and a transcript of the recording for each of the two periods was obtained for analysis.

RESULTS

A total of 168 flashes was reported: 24 during the first session and 144 during the second. Figure 1 shows a plot of the trajectory ground tracks for both observation sessions with each light flash occurrence marked. The numbers shown in the South Atlantic Anomaly on the ground track for session number two indicate the number of flashes observed during one minute intervals. Because the frequency of flashes in the South Atlantic Anomaly was much less in session number one, event marks instead of numbers were used.

It is almost impossible, because of the relatively few flashes observed and because of varying lengths of time spent at different latitudes, to show in a simple way the relationship between flash occurrence and geomagnetic latitude or HZE flux. However, figures 2 and 3 attempt to demonstrate this for the two observation sessions. As can be seen by referring to figure 1, time from equator passage is directly related to latitude. The calculated cosmic ray flux for latitude positions of the spacecraft corresponding to the times from equator passage is shown on both figures 2 and 3. Although there is evidence for correlation of flash occurrence with cosmic ray flux (or geomagnetic latitude) in figure 2, figure 3 more clearly demonstrates this relationship. The Van Allen belt dosimeter data for the observation periods are also shown on figures 2 and 3. The units shown on the ordinate of figures 2 and 3 do not apply to those curves; instead only relative units need to be visualized. It is apparent that the flash rate in the South Atlantic Anomaly coincides remarkably well with the increased radiation levels detected by the Van Allen belt dosimeter.

COMMENTS AND CONCLUSIONS

Although a few light flashes were reported as casual observations by the crews of Skylab 2 and Skylab 3, the events reported here represent the first observations made in Earth orbit. No flashes were observed during previous Mercury or Gemini flights or duing Apollo missions prior to Apollo 11. Why no flashes were observed prior to Apollo 11 has been considered before (1) and even now no clear explanation exists. The most logical explanation appears to be that the eye must be dark adapted and the observer must be reasonably relaxed and free from most distracting activities to observe light flashes. This was not the case

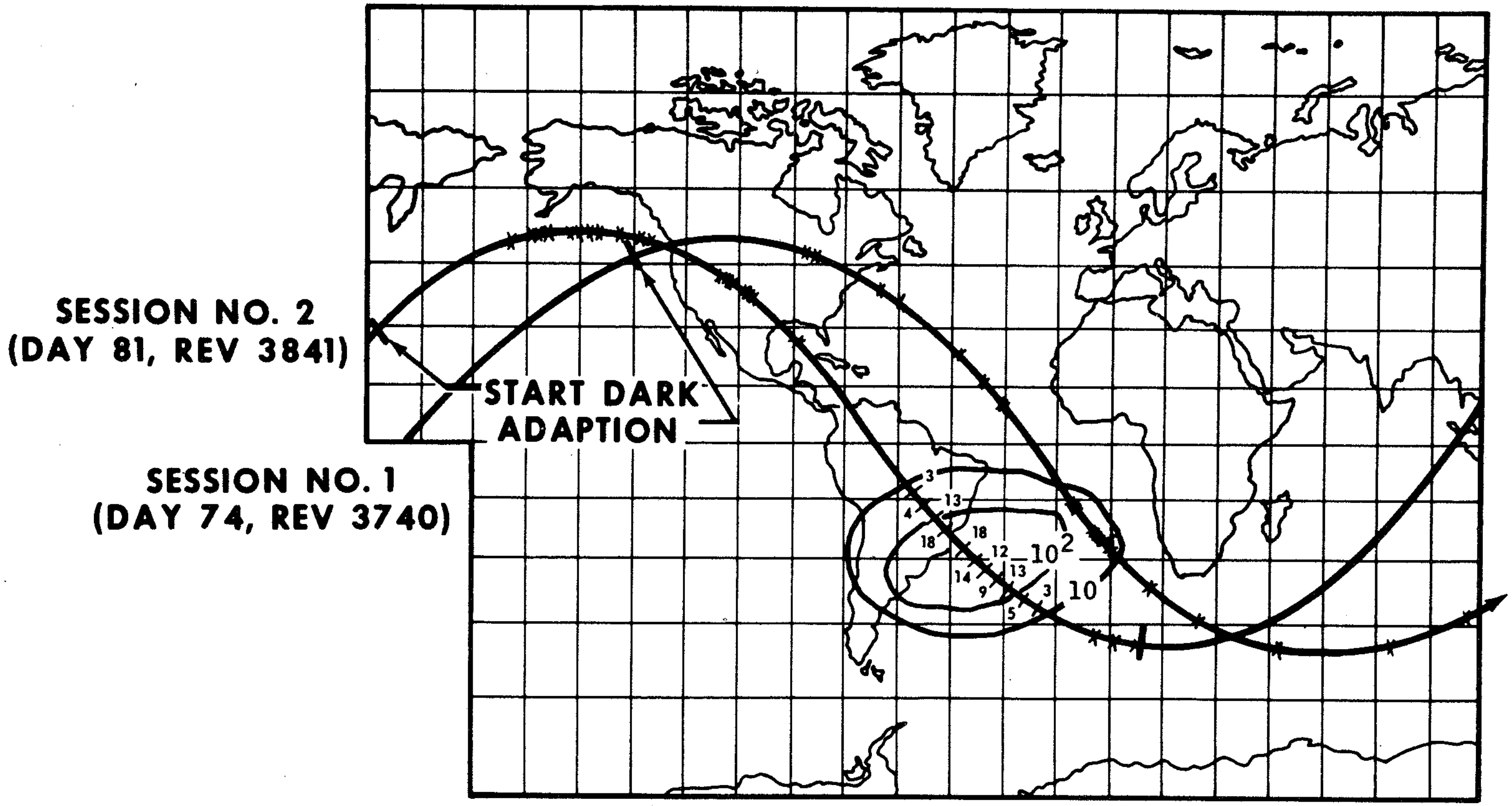
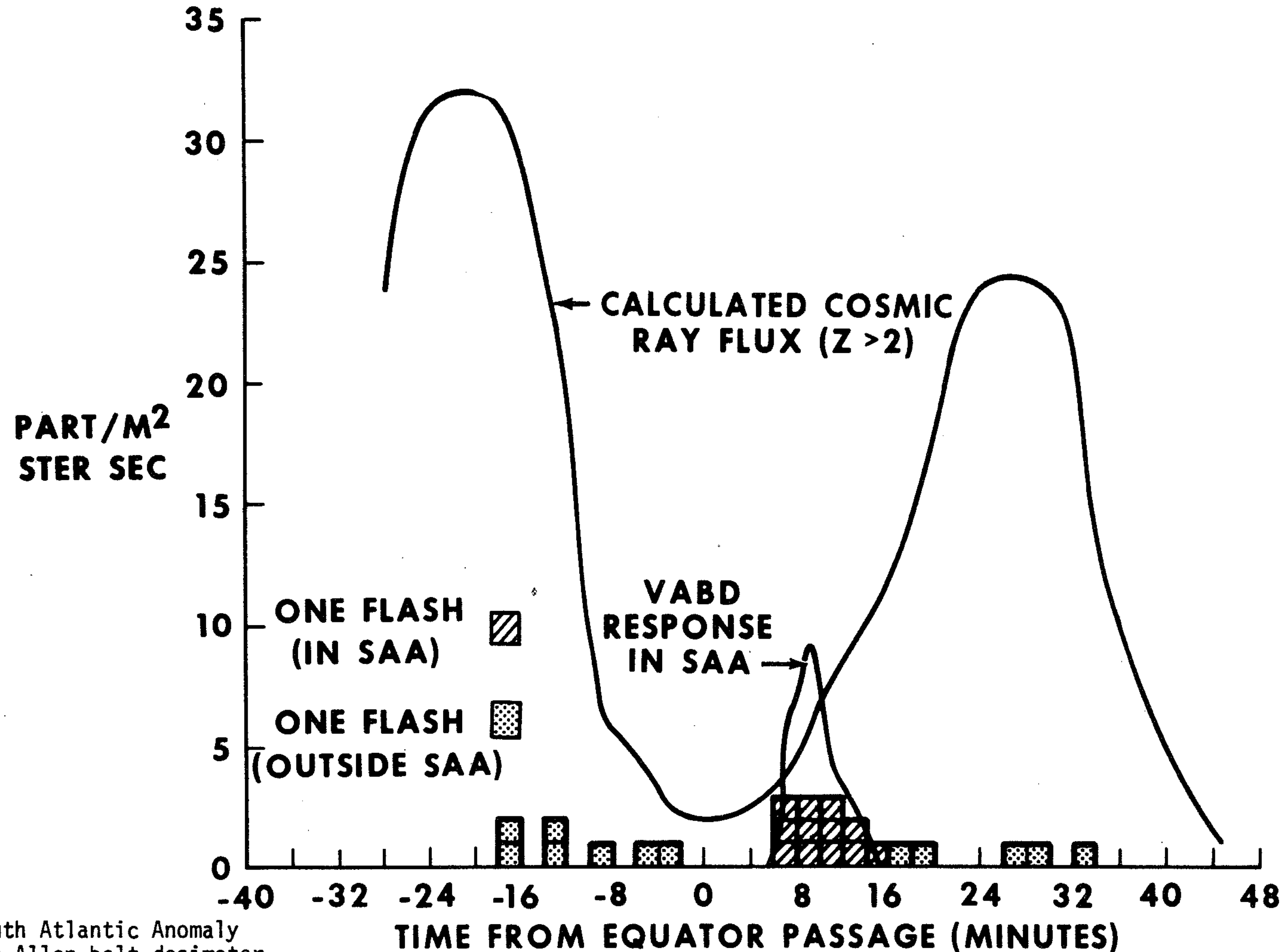


Figure 1. Event occurrences along ground tracks for the two Skylab 4 light flash sessions (Pilot-observer).



LEGEND:

SAA = South Atlantic Anomaly
VABD = Van Allen belt dosimeter

Figure 2. Skylab 4 light flash observation. Session no. 1.
(Mission Day 71; Rev 3740)

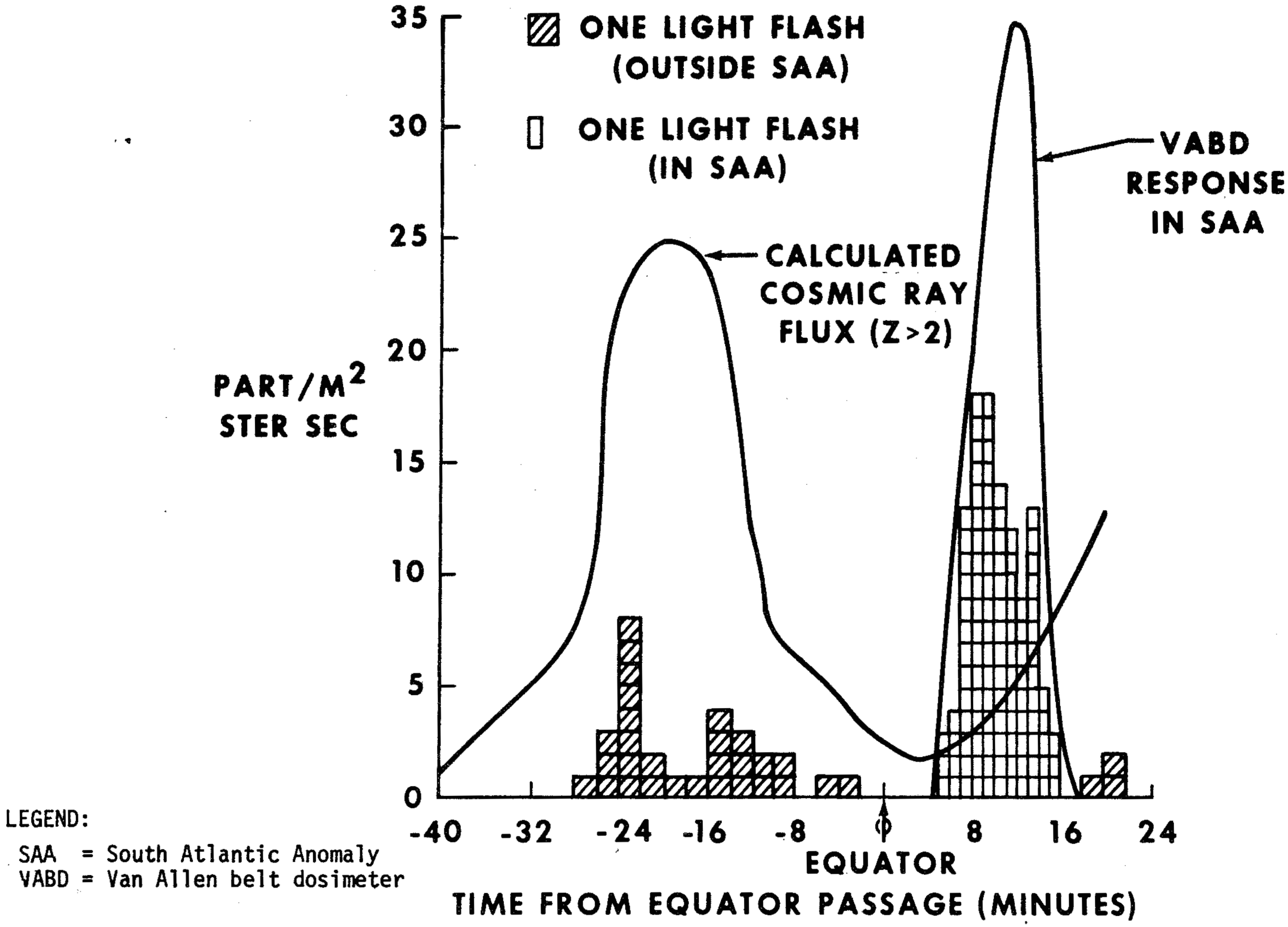


Figure 3. Skylab 4 light observation. Session no. 2. (Mission Day 84; Rev 3841)

on earlier flights. Also without a precedent for their observation, there would probably be the tendency to discount minor flashes as nothing unusual and simply an innocous event in a milieu of more important observations. It seems obvious now that with eyes trained for observing these events their occurrence will be noted whenever proper conditions exist.

The following conclusions can be drawn from the data presented:

- Dark adaptation of at least 10 minutes duration is required to begin observing the flashes.

- There is a strong correlation of very high flash rates with passage through the South Atlantic Anomaly, and, from physical arguments and event descriptions, it appears certain that these flashes are due to the trapped radiation.

- There is evidence for the predicted latitude effect, although existing data are insufficient for a thorough statistical evaluation.

- A greater particle flux in the trajectory through the South Atlantic Anomaly during the second observation period probably explains the increased number of flashes observed at that time, but there were also more flashes observed outside the anomaly during this second period where the cosmic particle environment should have been comparable. This variation remains unexplained at this time.

There is an additional suggestion from the event rates and descriptions of flashes during the South Atlantic Anomaly passes, that there may be particles heavier than protons in the inner belt of trapped radiation. The current knowledge of the inner belt includes an upper limit of only approximately 1 heavy nucleus per 1000 protons. The Skylab 4 light flash data are compatible with this limit, but still suggest the existence of a significant flux of $Z \geq 2$ particles. This provides strong motivation for making detailed and accurate measurements of the South Atlantic Anomaly (inner belt) heavy component.

The observation of flashes during space flight reported here and those reported previously represent very few events from a statistical standpoint. More such observations need to be made and are planned[1] for the Apollo-Soyuz Test Program mission. Although there is a basic

[1]Experiment MA106: Principal Investigator - Dr. T. F. Budinger

interest in studying the visual flashes *per se*, the real importance to manned space flight is the question of their significance. Are they mere flashes similar to other visual observations we make continually and represent no danger? Does each flash signify the destruction of one or more retinal cells? Are the flashes observed and the resultant damage, although potentially serious in itself, indicative of even more damaging interaction of HZE particles with other tissues, *e.g.*, the brain? The need for extensive ground investigations using accelerator produced radiation is apparent. Space observations as reported here must serve as guidelines for ground studies currently underway and others yet to be conducted.

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CHANGES IN THE ACHILLES TENDON REFLEXES FOLLOWING SKYLAB MISSIONS

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ABSTRACT

A generalized hyperreflexia was clinically reported in the crew of the first manned Skylab mission. To assess possible neuromuscular alterations following extended space flight a decision was made to conduct duration measurements of the Achilles tendon reflex and its associated muscle potential. Reflex duration was measured from the initial stroke upon the tendon until all oscillations had ceased. The muscle potential interval for each reflex was measured from the initial tendon stroke to the point of greatest amplitude of the muscle potential spike. Crewmembers of Skylab 3 and 4 exhibited a significantly ($P<0.01$) shortened reflex in the immediate postflight period. A compensatory prolongation of the reflex duration was exhibited between 4 and 12 days after recovery followed by a gradual return to the preflight values. In general, the muscle potential interval corresponded with the increase and decrease in the reflex duration.

INTRODUCTION

A generalized hyperreflexia was reported in the crewmembers of the first Skylab mission during the immediate postflight clinical evaluations (1). This finding supports earlier reports of an increase in reflex amplitude by Soviet researchers (2). To document possible neuromuscular changes, a decision was made to conduct measurements of the Achilles tendon reflex during the subsequent Skylab missions.

Various devices have been utilized to measure the Achilles reflex duration. Some of these devices are a light beam and photocell arrangement; capacitance changes and various types of mechanical transducers. Reported normal duration time for the Achilles reflex varies widely and depends heavily on the transducer type and interpretation of the data by the investigator. Nordyke, *et al.*, (3) report normal reflex durations from 250 to 410 milliseconds while Bowley, *et al.*,(4)

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report a normal range of 160 to 280 milliseconds. Such wide variation in reflex durations dictated that each crewman serve as his own control in the experiment.

The present study is an attempt to quantitate in time

- ° any changes in the duration of the Achilles reflex relative to extended space flight, and
- ° the duration of the muscle potential associated with the reflex.

METHODS AND MATERIALS

Each one of the Skylab 4 crewmembers participated in three preflight and six postflight tests. On Skylab 3 crewmen, one preflight test (F-5) and four postflight tests were obtained. The postflight tests were done immediately on recovery day and thereafter on a regular basis at the end of Lower Body Negative Pressure (M092) experiments. The schedules for Skylab 3 and 4 tests were as follows:

Skylab Mission	Preflight (days)	Postflight (days)
3	F-5	R+0, R+4, R+16, R+29
4	F-30, F-15, F-5	R+0, R+1, R+5, R+11, R+17, R+31

In a typical test session, the erect crewmember positioned his right knee on a firm support, with additional support as necessary, to achieve relaxation of the gastrocnemius muscle. A relative displacement transducer was firmly attached to the plantar bearing surface. Three electrode sites were prepared on the midsection of the gastrocnemius muscle to obtain muscle potentials, and silver electrodes of two centimeter area were fixed to these sites with a conducting gel. The Achilles tendon was struck several times as a warm up and to check the gain setting of the recorders. The signals from both the displacement transducer and the electrodes were amplified and recorded simultaneously on strip chart and FM magnetic tape. To elicit reproducible and well inscribed tendon reflexes the Achilles tendon was struck every two seconds for thirty seconds with a precussion hammer. No reinforcement maneuver was used to augment the reflex.

Data Analysis

For each experiment, an average number of twelve complexes on strip chart were analyzed. The Achilles reflex duration was measured from the initial stroking of the tendon until all movement had ceased. This method of determining duration should detect change occurring in the contraction and/or relaxation phases of the reflex. The muscle potenial interval for each reflex was measured from the beginning of the mechanical upstroke to the point of greatest amplitude of the muscle potential spike (fig. 1).

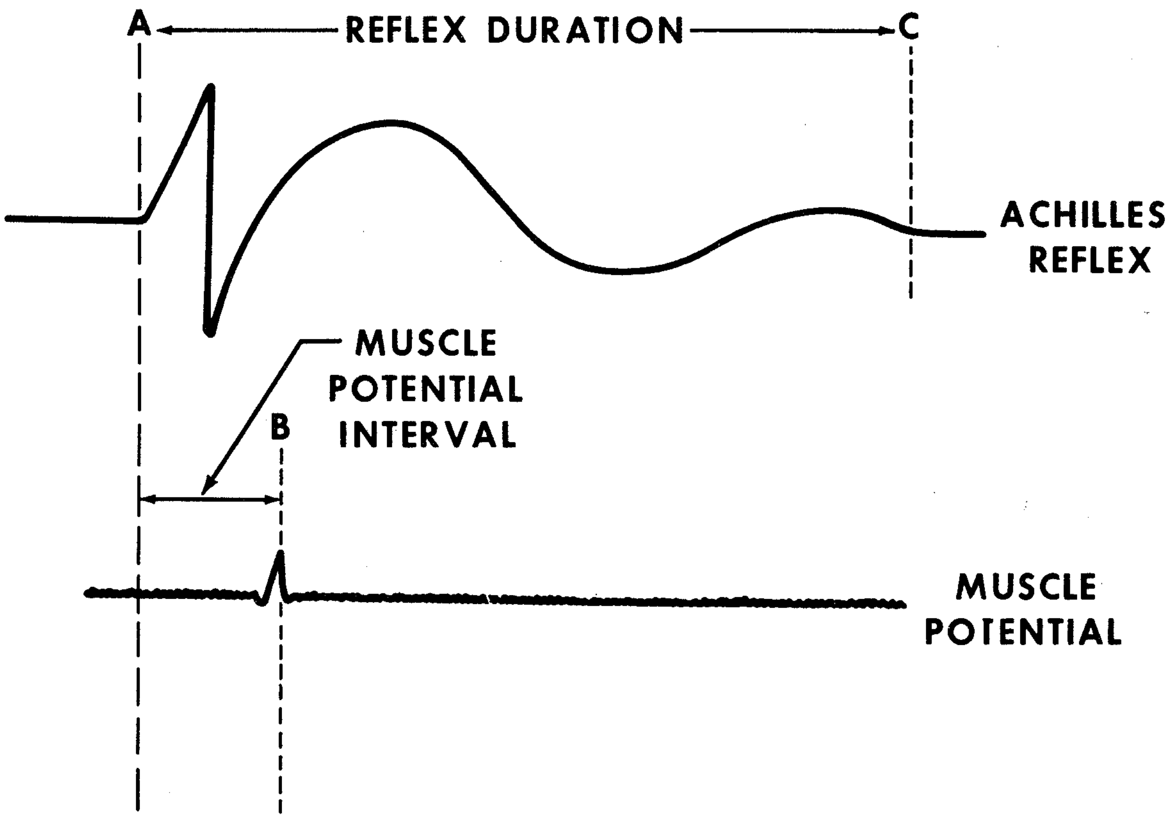

Figure 1. Illustration depicting method of measurement of the reflex duration and muscle potential intervals.

For the Skylab 3 mission the mean and standard deviation were computed for both the Achilles reflex duration and the muscle potential interval. Student's t-test was used to determine if any postflight data was significantly different from the preflight data.

For the Skylab 4 mission fiducial limits for the normal were calculated since a preflight baseline consisting of three separate test values was available.

RESULTS

The results of the single preflight and the four postflight tests for the Skylab 3 mission are presented in figure 2. The duration of the Achilles reflex immediately postflight showed a significant ($P < 0.01$) shortening for all three crewmen. The reflex duration exhibited further significant shortening on the fourth day after recovery. At the sixteenth postflight day there was a significant ($P < 0.01$) lengthening of the reflex for the Scientist Pilot and Pilot while the Commander showed lengthening which was not quite statistically significant. By 29 days post recovery, the reflex duration of the Commander had essentially returned to its preflight value. However, the Scientist Pilot and Pilot continued to show a significant lengthening of the reflex duration with a suggested trend toward their preflight values.

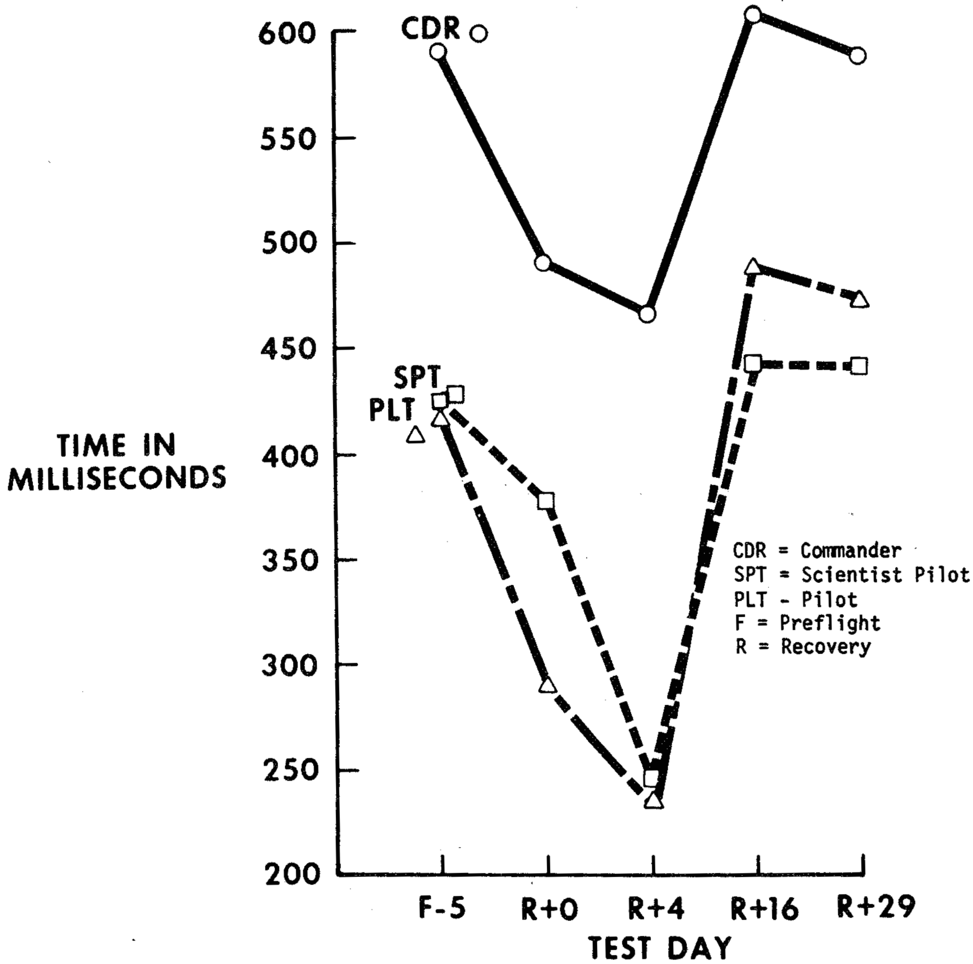

Figure 2. Duration of the Achilles tendon reflex for the Skylab 3 crewmembers.

The results for the Skylab 4 mission are presented in figure 3. The Commander showed an initial shortening of his reflex time that was within his preflight baseline. By the 5-day postflight test there was a significant lengthening of his reflexes well outside the fiducial limits of his baseline testing. In subsequent tests the Commander's reflex time decreased slowly until he was well within his baseline values by the 31-day postflight test.

The Scientist Pilot presented reflex times shorter than his baseline limits on recovery day. The reflex time lengthened on day 1 and by day 5 postflight it had increased to the point of being greater than his baseline limits. Subsequent testing showed an oscillating reflex time which by the 31-day postflight test had returned to within baseline limits.

The Pilot showed an immediate decrease in reflex time on recovery day. This condition lasted through the day 5 test. At the postflight day 11 test there was a significant lengthening of reflex times. In subsequent tests the Pilot's reflex times decreased until he was within his baseline limits by day 31 postflight.

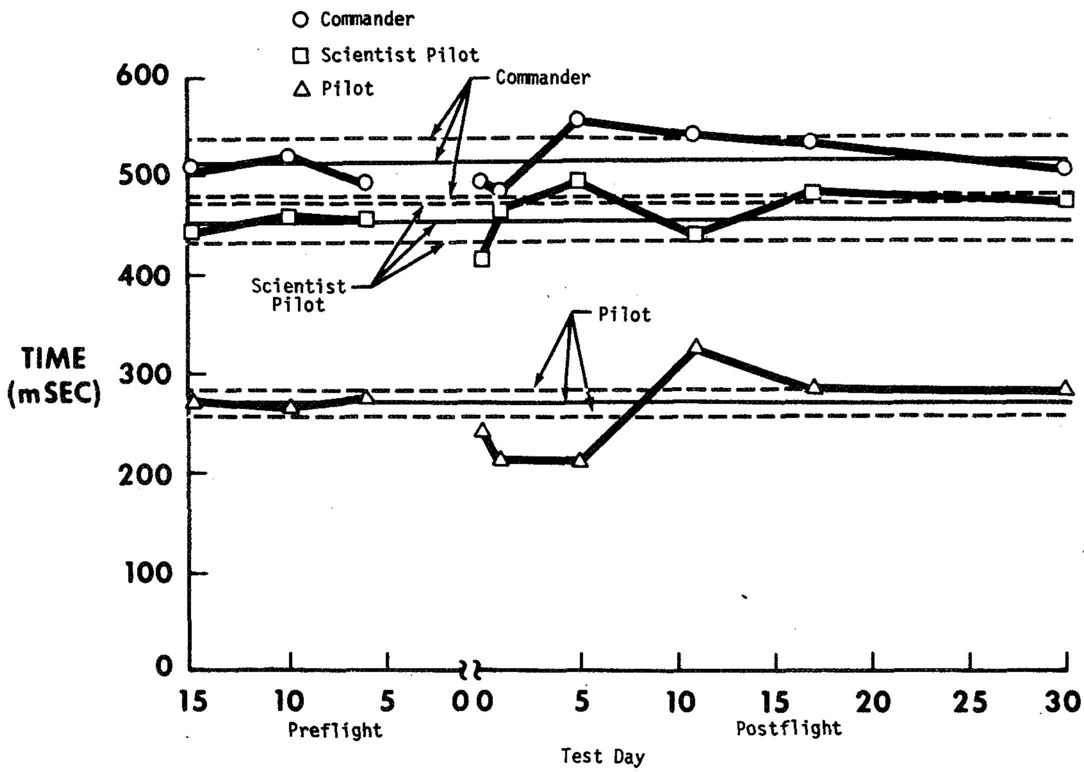

Figure 3. Duration of the Achilles tendon reflex for the Skylab 4 crewmembers.

The muscle electrical component of the reflex for the Skylab 3 mission proved to be difficult to obtain on the Scientist Pilot and Pilot. However, a full set of data was obtained on the Commander (fig. 4). The course of the Commander's postflight muscle potential interval paralleled his reflex duration, *i.e.*, the first two tests showed a shortening of the time interval while the last two tests showed a slowly increasing time interval not quite reaching his preflight value. Despite spotty data, the other two crewmembers also showed a similar response in muscle potential intervals.

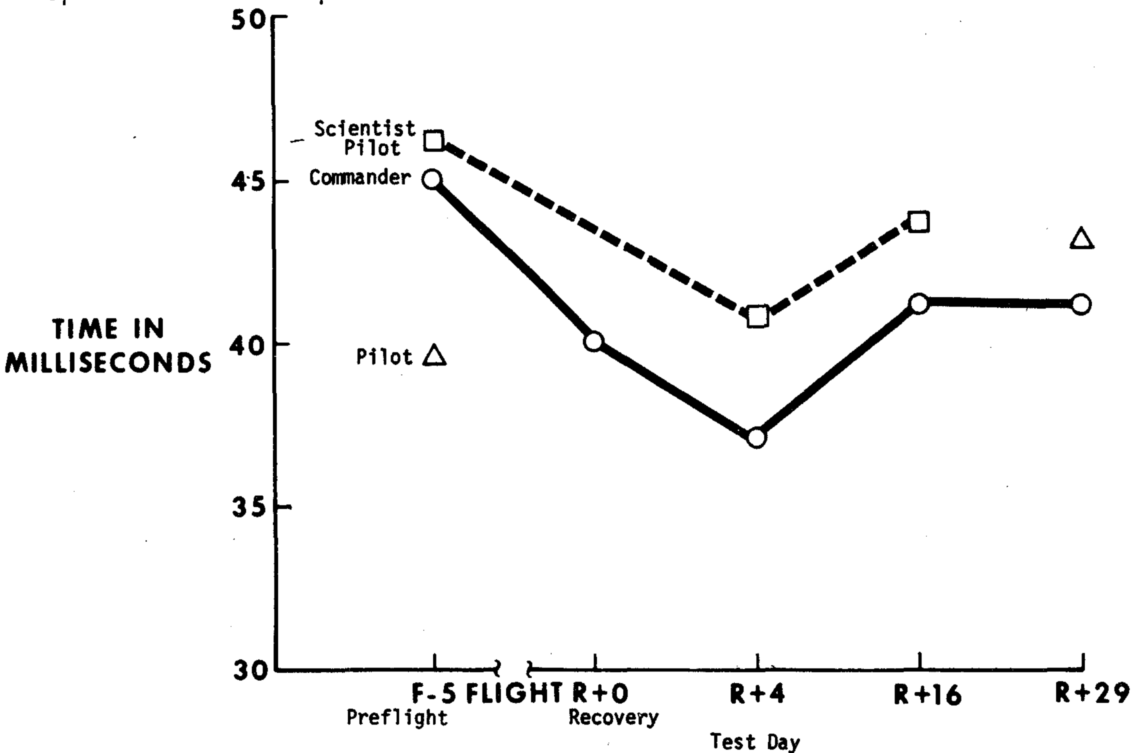

Figure 4. Muscle potential intervals for the Skylab 3 crewmen.

The electrical component of the reflex still proved difficult to obtain on the crewmembers of the Skylab 4 mission. No data were collected on the Pilot but fairly complete data were obtained on the Commander and Scientist Pilot. Inspection of the muscle potential intervals shows good agreement, *i.e.*, when the reflex time increased the muscle potential interval increased and *vise versa* (fig. 5).

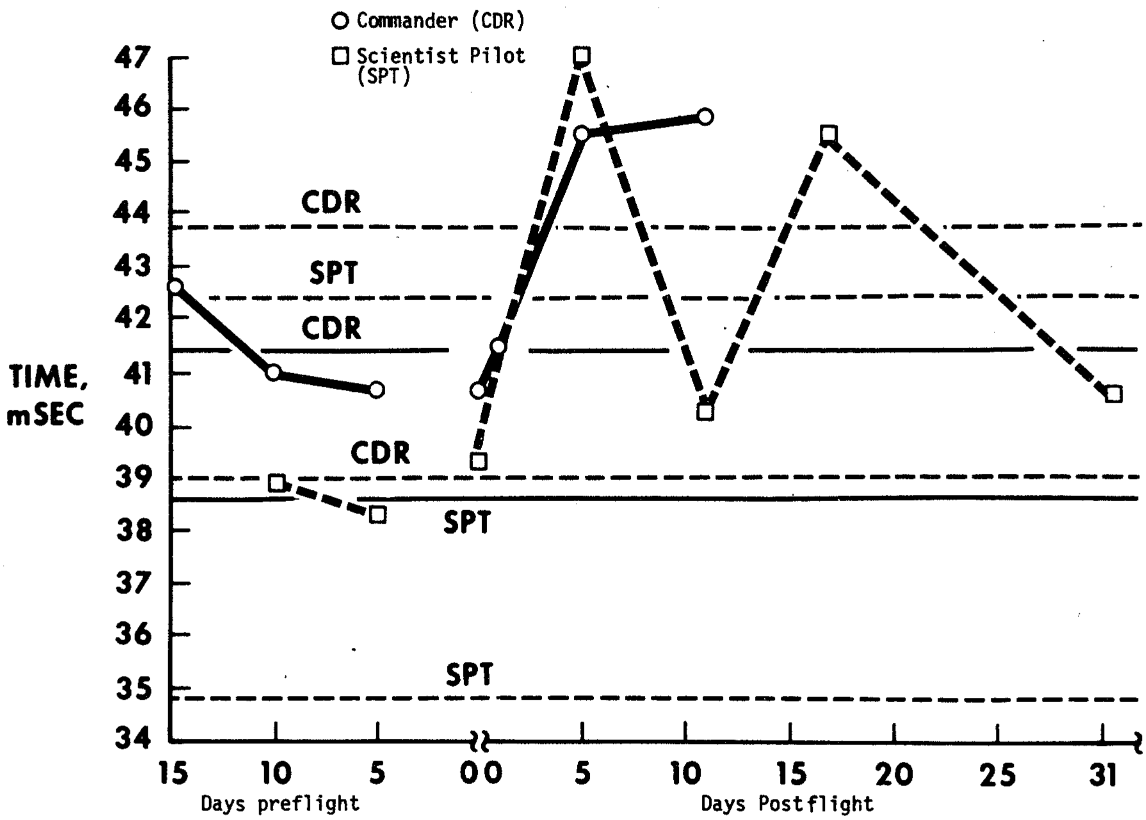

Figure 5. Muscle potential intervals for the Skylab 4 crewmen.

DISCUSSION

The six Skylab crewmen tested and some of the Cosmonauts have exhibited similar findings. These findings include a peculiar gait upon return to one-g field; muscular soreness and weakness; overcompensation in movements while in a vertical position and changes in the reflexes. While a fully satisfactory explanation for these neuromuscular findings is still lacking, several factors have been implicated.

Dealing specifically with the alterations in reflex times it might be postulated that an imbalance is present between the postural muscle groups. These muscle groups specifically support the body against the pull of gravity and if not adequately exercised might be expected to undergo selective relative disuse atrophy in a weightless environment. After return to the Earth's gravitational field, following partial or total acclimatization to weightlessness, the sudden burden imposed on these muscles could possibly result in a state of disequilibrium between the flexor and extensor groups. This gravity stressor may be

implicated in the altered reflex durations seen in the Skylab 3 and 4 crewmen. Interestingly, the reflex duration had approximately returned to preflight values at the time muscular soreness disappeared and the gait had returned to normal.

Another causal possibility is that of interaction between biochemical and hormonal factors and reflex duration. In the second manned Skylab mission the postflight thyroxin and epinephrine values were reported to be slightly elevated (5) which conceivably could account for some of the changes seen in reflex duration. An increase in both calcium and potassium was noted the first two days postflight and there was a transient increase in the concentration of ionized serum calcium (6). It seems unlikely, however, that these biochemical and humoral changes would affect the reflex durations for the time periods seen here.

It is interesting to observe that the crews of the Skylab 4 mission seemed perhaps slightly less affected, as regards reflex durations, by their increased time in space. There is also the added factor of progressively increased exercise regimens, both on the bicycle ergometer and the other devices (minigym Skylab 3 and 4, "Treadmill" Skylab 4).

CONCLUSION

At this point, the best explanation for the changes in reflex duration is perhaps related to the servofeedback system of the postural muscles themselves. These muscles, after weeks of inactivity and a loss of mass, must suddenly resume upright support of the body in a one-g environment, with an attendent strain and stretch in these muscles resulting in an over stimulation of the neuromuscular system causing the initial decrease in reflex duration. As the muscles regain strength and mass (7, 8) there occurs an over compensation reflected by the increased reflex duration. Finally, when a normal neuromuscular state is reached the reflex duration returns to baseline value. In general the available data seem to support this proposed hypothesis.

ACKNOWLEDGEMENTS

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TASK AND WORK PERFORMANCE ON SKYLAB MISSIONS 2, 3 AND 4
(Time and Motion Study - Experiment M151)

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ABSTRACT

The purpose of the Time and Motion Study experiment (M151) was to study the effects of the Skylab environment on a variety of work tasks involving different types of activity. In-flight crewman performance, sampled over the duration of the mission, was compared with corresponding preflight training data in terms of efficiency and possible behavioral stress effects associated with length of exposure to the working and living conditions of the Skylab environment. Experimental data were acquired through motion-picture film and video tape, and time and motion analytic techniques were used to study the data. Efficiency was evaluated by using the adaptation function, namely, the relation of performance time over task trials.

The basic finding from this experiment was the uniformity of crew performance over the three missions. Initial changeover from preflight to in-flight environment (or from one-g to zero-g) was accompanied by an increase in performance time for the majority of work task activities studied. By the end of the second in-flight trial, more than half of the activities were performed as efficiently as on the last preflight trial; performance proficiency increased during each Skylab mission. In general, crewmen adjusted rapidly to the weightless environment and became proficient in developing techniques to optimize task performance.

Performance time varied with method change and with task and hardware configurations. The use of arms and legs (and the entire body) as subtle guidance and restraint systems facilitated the efficient translation and control of large and small masses, including the crewman himself. Differences in crew performance were not pronounced; variations in training procedure, the natural tempo and style of each crewman, and method changes were critical explanatory factors.

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INTRODUCTION

The purpose of the Time and Motion Study was to determine how well man can perform specified tasks under zero-g conditons over the course of long-duration space flights. Among its objectives, experiment M151 studied the in-flight adaptation of crewmen to a variety of task situations involving different types of activity. Training data provided the basis for comparison of preflight and in-flight performance.

It was anticipated that in-flight performance of some tasks would be but slightly affected, while the performance of others in the zero-g environment would exhibit more pronounced changes in time and/or in the patterning of the elements comprising the tasks. On the assumption that overall work time would increase in the zero-g environment, initially at least, an additional objective was to determine at what point work efficiency in-flight would be restored to that manifested during the last preflight performance.

The adaptation function, or, the relation expressing the amount of time it takes to perform the same task in successive trials (task time as a function of task trial), was used to evaluate the effect of the Skylab environment on task performance. As graphed, this function is represented by a curve which decreases (*i.e.*, performance time gets shorter) from trial to trial, ultimately reaching a point where successive trials yield similar values (*i.e.*, approach to asymptote). The rate of decrease, which indicates improvement, differs for different tasks. The character of this curve also varies from individual to individual. Unexpected changes in slope or in variability can be used to identify difficulties with hardware, changes in environmental conditions, or alterations in method of performance. Change in performance level or in variability may also reflect fundamental changes in the attitude or physiological condition of the subject. The adaptation function can also be used to identify the point at which in-flight task efficiency is restored to the level of preflight proficiency. It also provides a basis for developing criteria of performance deterioration, specifically relevant to space flights of long duration.

OBJECTIVE OF PRESENT REPORT

The specific objective of this report was to present data on those work and task activities encompassed by experiment M151 and common to Skylab missions 2, 3, and 4. The emphasis, then, was on the replication and comparison of crewman performance on flights of varying time lengths. It was thus possible to study the effects of increasing performance trials on the characteristics of the adaptation function.

Similarly the effect of increasing zero-g exposure on work and task performance was available for analysis.

DATA ACQUISITION

A Maurer 16 mm Data Acquisition Camera, supplied with S0168 color film, was used to photograph selected tasks on each mission. Two Maurer lenses were employed: a 5 mm lens with wide angle field-of-view to photograph activities in the lower area of the Orbital Workshop where the camera was constrained by close proximity to the filmed activity; and a standard 10 mm lens to photograph activities in the Orbital Workshop forward area. A portable high intensity light was used where onboard lighting was incapable of yielding acceptable photography.

On Skylab 2 all data were photographed at six frames per second to provide reliable criteria for determining the end points of the elements comprising the task. On Skylab 3, frame rates were reduced from six frames per second to two frames per second for some activities in order to conserve film for an adequate sampling of data over a mission twice the duration of the first. Mass handling tasks were maintained at six frames per second. Skylab 4 data collection followed the same guidelines as those for Skylab 3.

Illumination levels varied from four to nine foot-candles depending on location, and as has been mentioned, the portable high-intensity light was used only where onboard lighting was totally unacceptable for photography. Power conservation practices during early portions of Skylab 2 to relieve power and thermal problems, required some concessions in normal lighting levels, but usable data were obtained.

Because of accumulating radiation damage to film, new lighting criteria were initiated for Skylab 4. The increased use of portable high-intensity light in addition to normal lighting reduced the effects of radiation. Image enhancement procedures were also utilized to counteract radiation damage.

Film Analysis

Approximately 4350 feet of film were taken on Skylab 2, while more than three times this amount, 14 700 feet, were available from preflight training. Corresponding data for Skylab 3 were 3800 and 10 400; for Skylab 4, 2500 and 6800.

To process this large volume of film a three-level analysis procedure was developed to filter the data into classes according to the depth and detail of analysis required. With this procedure the film as a

whole was analyzed, but portions of critical importance were given detailed treatment.

The film was examined on a special film viewer which had the capability of controlling rate of presentation and alignment, while attaining high precision in measuring the dimensions and orientations of the image. In the first level of analysis, each task or activity was broken down into the elements required for its performance. These elements were identified and defined during the training sessions. Along with the basic identifying information, such as date filmed and analyzed, film rate, work activity, *et cetera,* the first level analysis gave the element description and the frame number or time at the end of each element.

The second and third levels of analysis built on the data obtained from the first level. More detail was provided and relevant accessory variables were identified. Thus, for each element the second level of analysis included torso configuration, position restraints, restrictions, detailed motion patterns, *et cetera.* The third level added to the second level such items as crewman elevation, roll and heading, plus details as to elbow, torso, and knee angles. From this information it was possible to reproduce in a quantitative fashion and to a high degree of fidelity the patterning and temporal course of any activity.

The work of the film analyst was facilitated by the use of a Coding Dictionary. The dictionary provided the necessary definitions for identifying, classifying, and measuring the activity as depicted on film. It gave exact instructions for computer coding - the data to assign to specific card fields, the use of various programing cards, and all other programing instructions. The use of the Coding Dictionary maximized the objectivity and accuracy of film analysis.

Task Selection

Selection of activities to be filmed was governed by a number of rather restrictive criteria. Repetitive and relatively standardized tasks were required to satisfy replication and uniformity conditions. At the same time, relevant and natural, rather than contrived, activities were desired. Consequently, they had to be part of the planned schedule, not added to or modified for experiment M151. Additionally, variety in tasks was sought in order to permit the study of a broad spectrum of human performance.

Activities associated with the preparation and execution of approved medical and scientific experiments met all of these requirements. Thus, the regularities of experimental procedures in other experiments provided M151 with a source of homogeneous data for analysis and evaluation.

Experiment Data Sources

The experiments and operational activities serving as sources for photographic data are listed below, together with a brief description of some of the activities of interest.

M092 Inflight Lower Body Negative Pressure. The preparation for this experiment involved the coordinated interaction of two men who utilized both fine and gross motor activity in the unstowing, preparation and donning of electrodes, probes, and measuring devices. In addition, precision of translation and ingress of the Lower Body Negative Pressure Device was required.

M171 Metabolic Activity. This experiment also involved a two-man interaction in the mounting of the ergometer and donning of the restraint system (which was deleted in-flight) and metabolic apparatus. Operations involving unstowing, assembling, and connecting required gross motor activity. Specialized restraint systems were utilized.

T027/S073 ATM Contamination Measurement - Gegenschein/Zodiacal Light. The removal, deployment, transfer, installation, and retrieval of the photometer (and associated activities) involved two-man interaction (reduced to one-man activity in-flight) in handling and translating with hardware of very large mass and size. The photometer weighed 95 kilograms and had dimensions of 140 x 50 x 30 centimeters. Gross and fine motor dexterity was involved in the varied activities associated with this operation.

S190B Earth Terrain Camera. The removal, preparation, installation, deployment, and retrieval of the Earth Terrain Camera required a one-man/mass interaction utilizing medium-sized hardware. The camera weighed 29 kilograms and had dimensions of 70 x 20 x 30 centimeters. Fine and gross motor activity was involved as well as translation with load.

S183 UV Panorama. Photography of this experiment yielded data encompassing unstowage, transfer, installation and film loading of large hardware which weighed 48 kilograms and had dimensions of 130 x 40 x 40 centimeters. Fine and gross motor activity was involved as well as translation with or without loads of varying size.

M509 Astronaut Maneuvering Equipment. One-man maintenance activity involved removal, stowage, unstowage, transfer and installation of hardware subassemblies. Two-man interaction in donning experiment hardware employed fine, medium and gross motor activity.

EVA Suit Donning and Doffing. Donning of the suit from the Liquid Cooled Garment to pressurization required two-man interaction involving fine and gross motor activity. Suit doffing involved similar types of activity.

Food Preparation. Removal, collection, and preparation of food required relatively gross motor activity. Use of a thigh restraint was involved.

Not all of the data obtained from the tasks listed above were used in this report. The primary emphasis was on comparable data obtained from all three missions.

Sampling and Replication

Weight and stowage restrictions placed a limit on the amount of film assigned to experiments. The crowded complexity of an astronaut's workday presented schedule difficulties for filming the desired experimental trials. These constraints created problems of sampling the experimental trials and allocating them to the Skylab missions.

On the Skylab 2 mission, sampling density was maximized for the initial group of trials of an experiment. During Skylab missions 3 and 4 more emphasis was given to performance towards the end of the mission, to better detect performance variability, should any have occurred due to extended exposure to the Skylab environment.

It will be observed that the final or last trial was not generally used for filming. There were two reasons for this decision. In the first place, the well-documented "end-effect" was avoided. This effect, observed in traditional learning as well as in isolation situations, reflects the frequently occurring change in attitude of the subject as he realizes that this is his last trial, or last day of isolation. Thus toward the end of a flight, the attitudes and interests of the astronauts were expected to become more focused on "cleaning up" or "getting ready to leave". The second reason was concerned with the practical matter of work slippage. Small but annoying problems could develop during the course of a mission with the result that experimental trials late in the series might have to be sacrificed.

Preflight training involved the crewmen in various types of work and task performance. First, there were walk-throughs, then heavily assisted performances, and finally the crewmen on their own with very little or no assistance from training personnel. These latter performances, the last four or five before flight, were used as baseline or contrast data for comparison with in-flight performance. The data points comprising the baseline extended over a period of many months,

from December 1972 to May 1973 for Skylab 2, from August 1972 to June 1973 for Skylab 3, and from November 1972 to October 1973 for Skylab 4. There were, of course, earlier training sessions. In M092, for example, the Skylab 2 crewmen as observers had a total of 25 training sessions; Skylab 3 crewmen, 14; and Skylab 4 crewmen, 27. The Skylab 3 crew had the fewest, approximately half the number of the other crews.

Time Measurements

The time to complete a task was measured in several ways. The most inclusive was Voice/Telemetry Time, the end points of which were either voice recorded by the crewman or automatically indicated by the start-stop controls of a timer. Thus, the beginning of a task may have been recorded by the statement "Started M092 at ____," while the completion of M092 data acquisition was automatically indicated by the crewman stopping the experiment timer. Termination was sometimes also announced by voice, as "End M171 at ____".

Camera Running Time included only the time during which activity was being photographed. It eliminated such preparatory activity as, arranging material for the experiment, making final calibrations, and other such activity which was included in Voice/Telemetry Time. Included in Camera Running Time, and in Voice/Telemetry Time as well, were such categories as foreign elements, waits and idles, anomalies, and redundancies. These categories will be discussed in more detail in the Performance Anomaly Section.

Basic Element Time was the least inclusive of the three measurement procedures, comprising the sum of the times associated with the basic elements. The basic elements were the set of elements which were necessary to complete the task; they appeared in every performance of the task, preflight or in-flight; and they were performed only by the crewmen to whom the task was assigned. Basic Element Time, then, was comparable from person to person, from mission to mission, and from preflight to in-flight performance. In contrast nonbasic elements were those which sometimes were omitted by the crewmen (*e.g.*, stow legbands), or modified, or done before the camera was activated or after the camera was turned off. In calculating Basic Element Time, such variables as foreign elements, waits, and idles which are defined in the next section were removed from the time for the element in which they occurred.

Element Time was the time determined for each element by time and motion techniques. This included basic as well as nonbasic elements. The time taken to complete each element listed in appendix A, at each task performance by each crewman, comprised the fundamental data source from

which special analyses were potentially available. As an example, elements could be grouped into classes, such as, fine or gross motor dexterity, translation with or without load, large versus small mass handling.

In the present report Voice/Telemetry Time measurements were included to demonstrate the type of adaptation function they produced. The major portion of the analyses, however, were based on Basic Element Time which provided valid comparisons across missions and between training and in-flight performance. Nevertheless, Voice/Telemetry Time provided a realistic estimate of the time it took to complete a particular in-flight task.

Performance Anomaly

The time required to perform a given task, subtask or element varies from performance to performance. Differences in method, procedure or motion pattern are also observed during task performance. These variations are due to a complex set of factors and where they are minor and no assignable cause (or causes) can be discovered, they are characterized as random. However, film analysis frequently reveals identifiable perturbations in task performance which have assignable causes. The situations giving rise to such perturbations have been categorized as: foreign elements, waits and idles, and task-related anomalies.

A <u>foreign element</u> is any activity or motion pattern unrelated to the ongoing task but initiated or caused by the crewman during the performance of the task. Examples would be a crewman stopping his task to take a message or to perform some other and more urgent activity. The time for foreign elements was recorded separately and removed from the time for the element (task) in which it occurred. These intrusive and task-independent activities may be occasioned by human lapses, needs, or distractions and by mechanical or hardware failure.

<u>Waits and idles</u> are characterized by breaks in the work cycle in which the crewman must wait for someone else to work with him, or for a mechanical process to be completed. Or the crewman may "take a break", or be idle, that is, nonproductive. He may also be engaged in mental activity (*e.g.*, reviewing progress) not observable to the analyst. As was done with foreign elements, waits and idles were removed from the time measurement of the task (or element) in which they occurred.

<u>Task-related anomalies</u> are those activities, initiated by a crewman, or by hardware difficulties, which occur during the performance of a task and are essentially a part of it. This class is represented by the "fumble", an incorrect procedure or sequence, a dropped object, or other task-related error. The time occupied by the anomaly is

usually included in the element time. If it is possible or advantageous to evaluate the causative factors involved, the anomaly can be treated as an element and isolated for more intensive study. As noted above for foreign elements and for waits and idles, task-related anomalies may have human as well as mechanical (hardware) origins. Task-related anomalies are of special importance in that they can point to deficiencies in the man/machine interface and/or in hardware design.

GRAPHIC RESULTS

One of the simplest, and in many ways most effective, methods of presenting experimental results is through graphic procedures. A representative picture of M151 data can be seen in a series of four graphs, figures 1 through 4, which depict the adaptation function for the basic activities involved in M092 Lower Body Negative Pressure, as these were performed on Skylab missions 2, 3, and 4. Training data comprise the left section of each graph; the right hand portion presents the in-flight results.

Figure 1 shows the results for the Pilot and Scientist Pilot as subjects in M092 Prerun Activity. The most striking feature of these graphs is the seeming continuity of in-flight performance as it followed the last preflight performance. The same tendency can be observed in figure 2 which summarized M092 Postrun Subject Activity, again for the Pilot and Scientist Pilot on each of the three Skylab missions.

The time to perform the basic M092 Prerun Observer Activity showed a different pattern in figure 3. In-flight performance was generally elevated in comparison to terminal preflight training data. This was most clearly shown in the performance of the Commander for each of the three missions.

In figure 4, in-flight performance time was at approximately the same level as that for preflight training data. Excepting the preflight performance for the Skylab 4 Scientist Pilot, the data showed very little variation.

Preflight training data for Skylab 3 and Skylab 4 was widely scattered over the twelve months preceding launch. In contrast, most of the training data for Skylab 2 was obtained within the last five months of launch time.

One important fact emerged from the analysis of the four graphs. Of the 23 in-flight curves presented in the four figures, 18 of them had their initial performance at a level higher than that found in the last preflight trial.

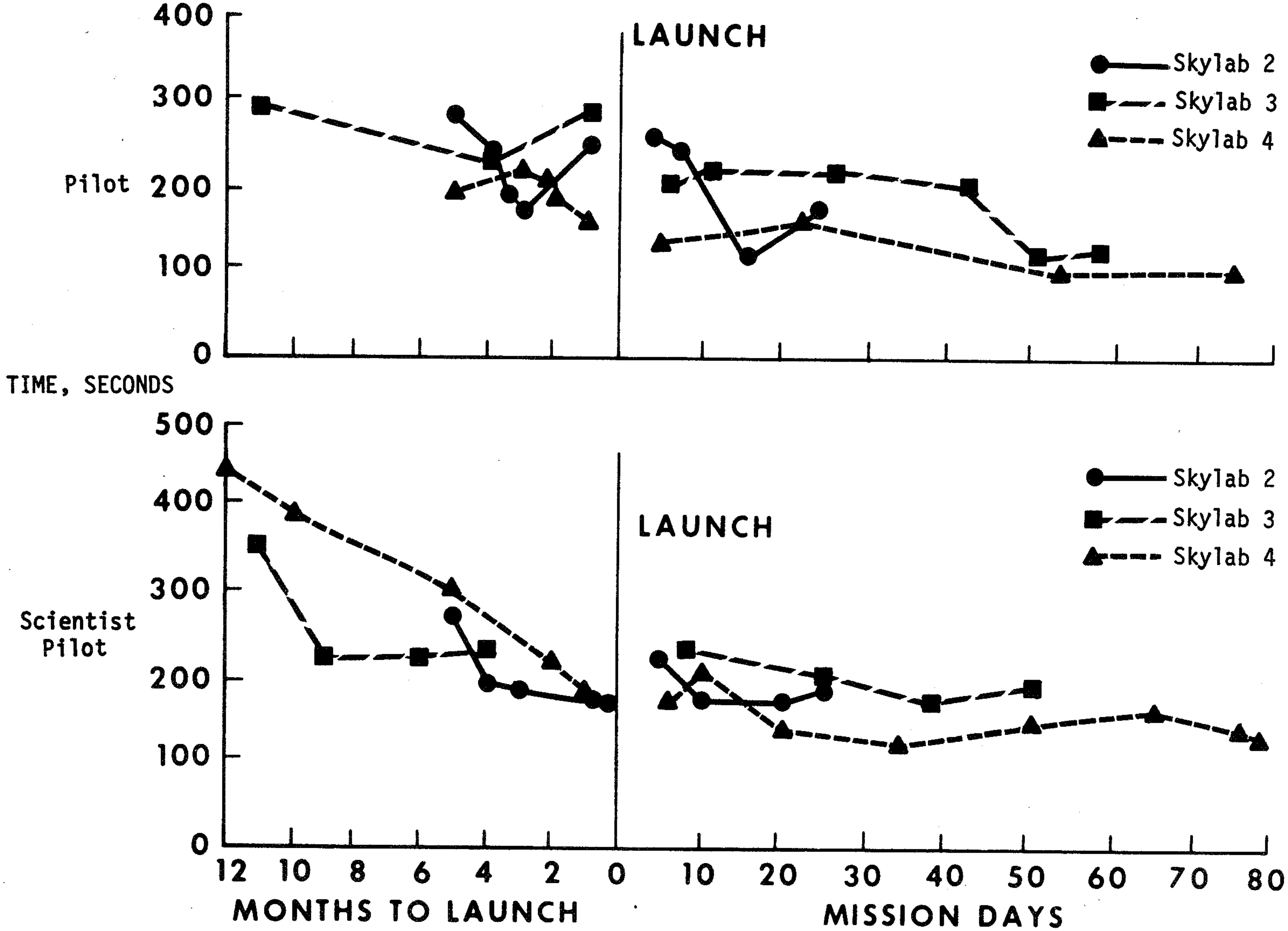

Figure 1. Time to perform basic M092 prerun subject activity.

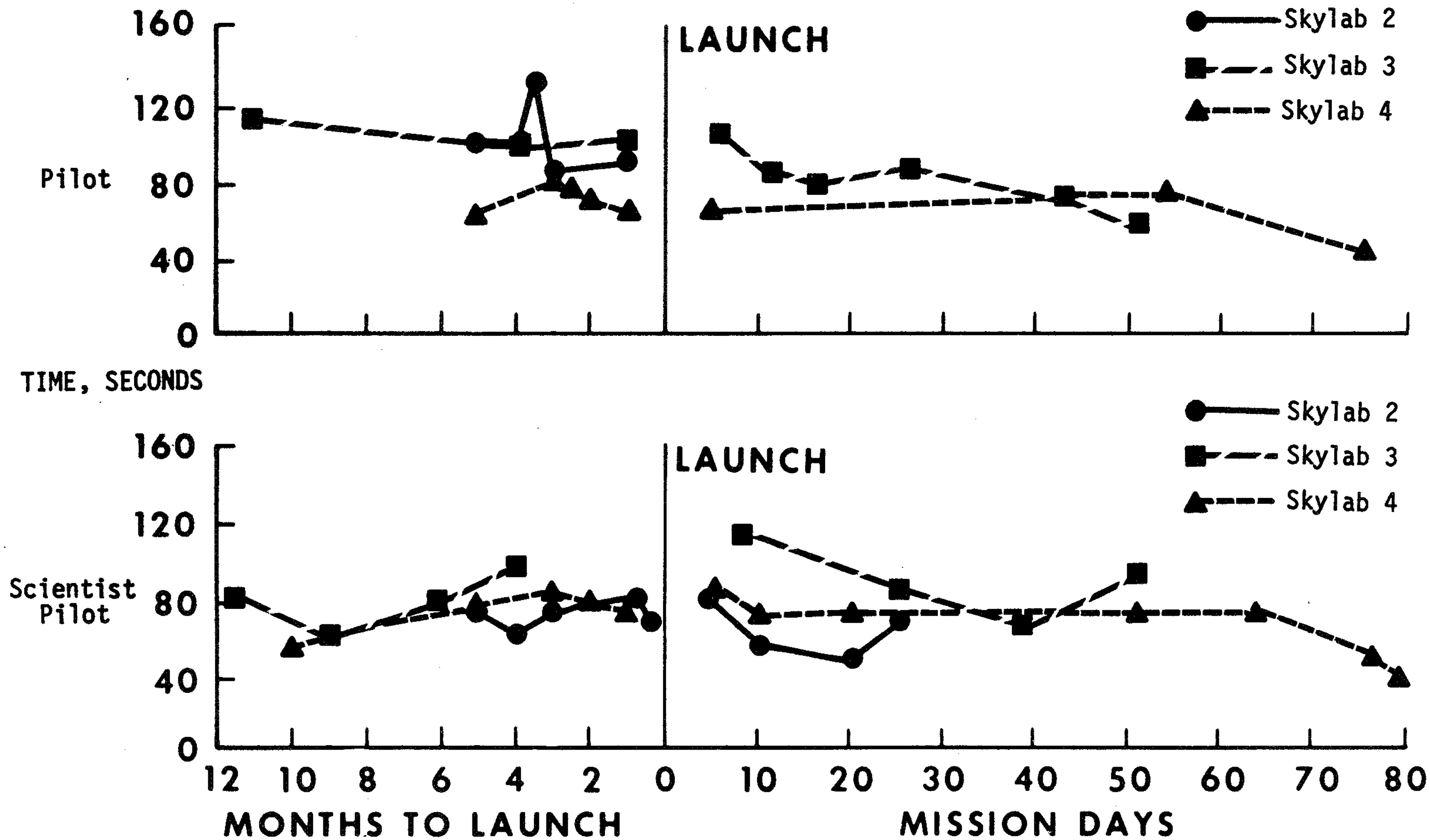

Figure 2. Time to perform basic M092 postrun subject activity.

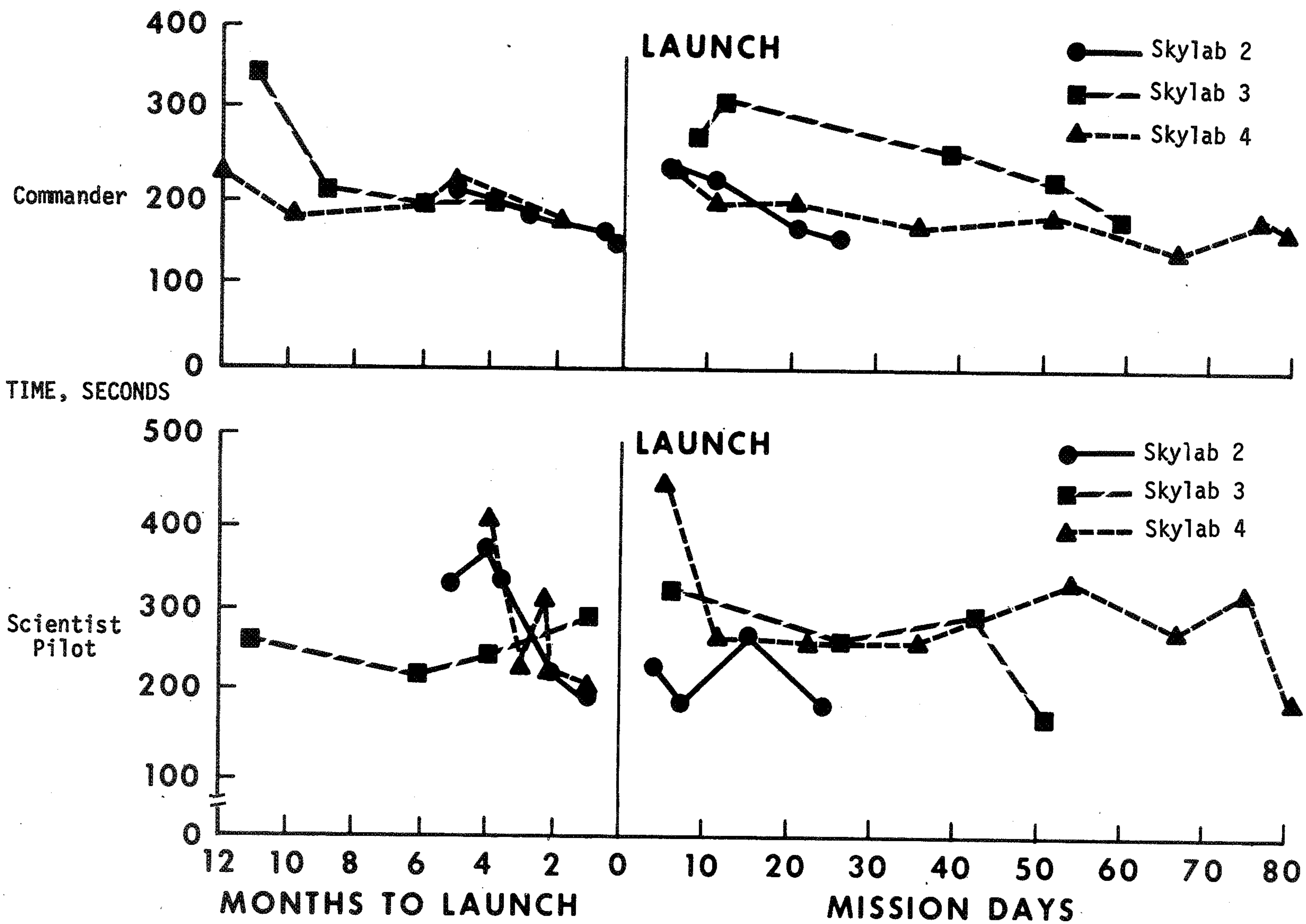

Figure 3. Time to perform basic M092 prerun observer activity.

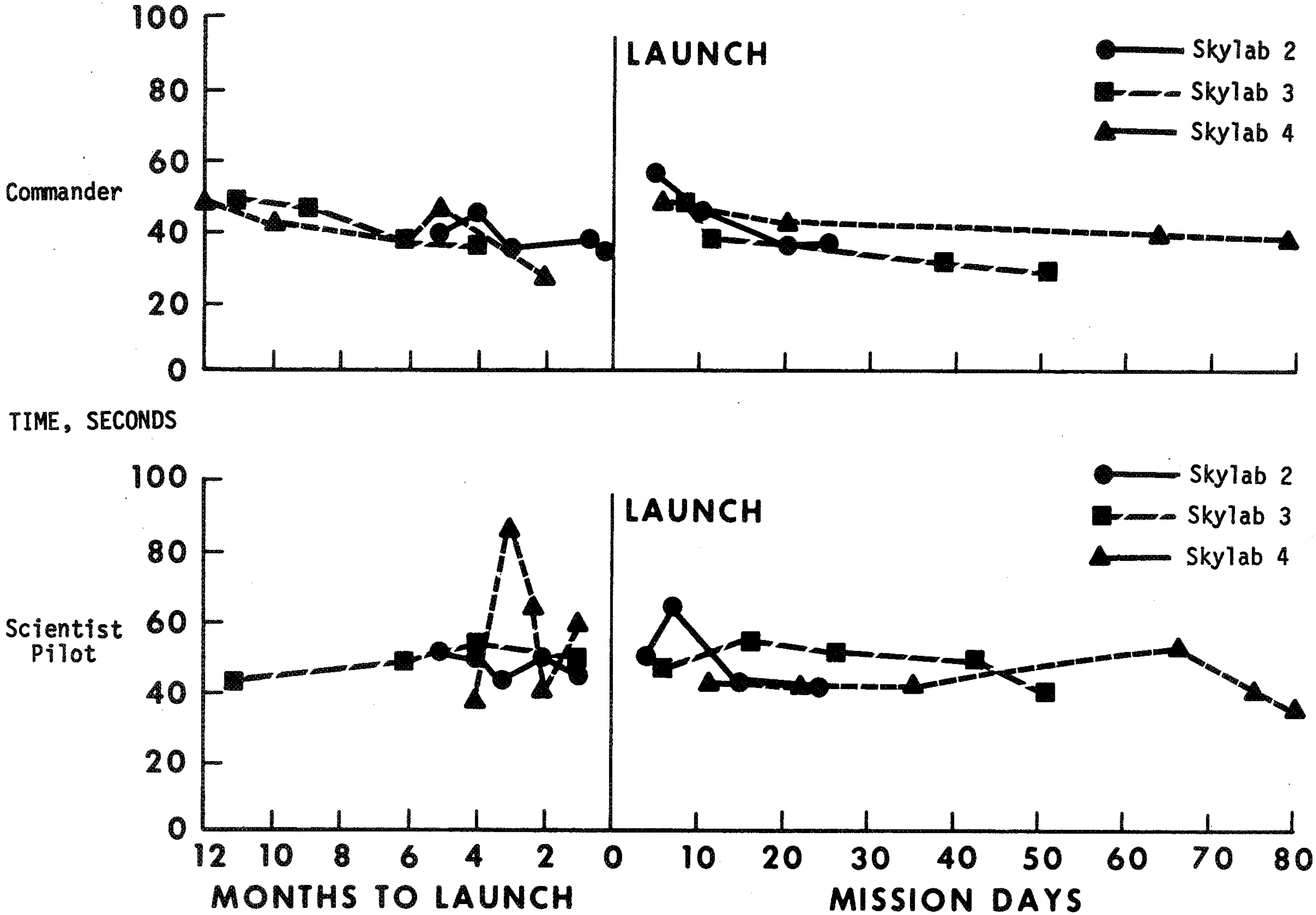

Figure 4. Time to perform basic M092 postrun observer activity.

(Scaling reflected the greater importance attached to in-flight performance. Providing larger units for Mission Days, made it possible for the in-flight performances to be more clearly differentiated among the three missions.)

STATISTICAL ANALYSES

First In-flight Task Performance

The first trial of an in-flight task was considered a significant datum for evaluating the effects of zero-g environment on task performance. In one sense, the zero-g effect was already diluted by the time the experiments began because crewmen had been busily working in the zero-g environment during the activation period, and for several days had been slowly divesting themselves of one-g habits and quickly acquiring zero-g maneuverability and expertise. Nevertheless, the previously presented graphs have strongly indicated that the first in-flight trial generally took longer than the last preflight trial of the same task.

To better evaluate the effect of the zero-g environment on the initial trials of in-flight performance, the tasks were subdivided into elements and the times associated with the performance of each element were compared, first trial in-flight versus last trial preflight. The data for these elements were presented in terms of frequencies, namely the number of instances that time for the first in-flight trial was greater than that for last preflight trial, and *vice versa*. The results are found in table I. Thus, in the Skylab 2 mission, 95 elements took longer to complete in-flight than preflight. For 44 elements, the situation was reversed. In 68 percent of the cases, then, the first in-flight trial took longer than the last preflight trial.

TABLE I. IN-FLIGHT (I) ELEMENT TIME (FIRST TRIAL) COMPARED WITH CORRESPONDING PREFLIGHT (P) ELEMENT TIME (LAST TRIAL) FOR THE SKYLAB MISSIONS

Skylab Mission	I > P		P > I		Percent (I > P)	
2	95	(36)[a]	44	(19)	68	(64)
3	61	(32)	52	(21)	54	(60)
4	94	(37)	66	(32)	58	(54)
Total	250	(105)	162	(72)	61	(59)

[a]Figures in parenthesis refer to Basic Elements only

Although the effect was not so pronounced for the remaining two missions, the results were consistent. When the results of the three missions were combined, it was observed that 61 percent of the first in-flight trials took longer than the corresponding last preflight trials.

Data in parentheses refer to Basic Elements. As shown in the table, percentages based on the basic elements appeared more consistent from mission to mission while summary results based on all three missions yielded almost identical percentages (59 versus 61).

The elements were also categorized into three classes representing tasks requiring fine, medium, and gross motor dexterity. Because of the consistency of results from mission to mission, the data were combined across the three missions. The basic comparisons, first in-flight versus last preflight, were thus available for the three types of motor activity involved in task performance. These are presented in table II.

TABLE II. COMPARISON OF PREFLIGHT AND IN-FLIGHT PERFORMANCE TIMES FOR ELEMENTS CATEGORIZED INTO FINE, MEDIUM, AND GROSS MOTOR ACTIVITY CLASSES

Type of Motor Activity Involved	First In-flight > Last Preflight	First In-flight < Last Preflight	Percent (I > P)
Fine	83	49	63
Medium	122	81	60
Gross	39	30	57

Although the first in-flight trial generally took longer than the last preflight trial, a result established in the previous analyses, the percent increase was most pronounced for fine motor activity, less so for medium and least for gross motor activity. The percentage differences are small and insignificant but the systematic decrement is important. Such a decrement would reinforce the debriefing comments of the astronauts who reported that the control of small objects caused more difficulty than the control of larger masses.

Return to Preflight Baseline

It has been noted that the first in-flight trial generally took longer to perform than the last preflight trial of the same task. The question arose as to how long it would take to adapt to the Skylab work environment, or more specifically, how many trials it would take before an in-flight task was done as speedily as it was on the last preflight

trial. The criterion of equivalent performance was taken to be that particular trial at which half or 50 percent of the task elements were done as speedily as in the last preflight performance.

The sources for this analysis were the activities involved in Experiment M092 (Prerun and Postrun, Subject and Observer), Experiment S073, and Suit Donning and Doffing. Table III presents the number of activities which, at first or second in-flight trial, were done as rapidly as they were on the last preflight trial. For example, by the end of trial 2, 44 of the 86 elements on Skylab 2 were completed within the time taken on the last preflight trial.

From an overall viewpoint, the results for the three missions were fairly consistent. When the elements were totalled across the three missions, exactly half of the elements returned to preflight baseline (last preflight trial) by the end of the second trial.

TABLE III. NUMBER OF ELEMENTS PERFORMED IN-FLIGHT (FIRST OR SECOND TRIAL) AS SPEEDILY AS ON LAST PREFLIGHT TRIAL

Skylab Mission	In-flight Time > Last Preflight	In-flight Time ≤ Last Preflight	Percent (I > P)
2	44	42	51
3	46	53	46
4	51	46	53
Total	141	141	50

The specific mission day on which the criterion was reached could not be precisely determined since some of the activities, such as Suit Don/Doff, were not scheduled as regularly as experiment M092. If one were to take experiment M092 as the more consistent indicator, then the mission day equivalences for the three flights were as follows:

Skylab Mission	Mission Day of Second Trial
2	7th or 10th day
3	8th day
4	10th or 11th day

In general, the second trial of experiment M092 was scheduled within the second week of the mission. It was anticipated, then, that the crewmen should have begun to feel adapted to their work schedules, or should have felt a reduction of the work pressure at about this time. The debriefing comments were not altogether clear on this point. For example, the Skylab 3 crew (and the Skylab 2 crew to some extent) indicated that the critical point in adaptation occurred in the vicinity of 10 days. As for the Skylab 4 crew, one member mentioned a period of a week or two, another a period of a month or so. From an objective viewpoint, however, the data suggested a point in time somewhere in the vicinity of a week or two.

The time period mentioned above was, in many respects, an artifact of work-schedule planning. There was some evidence in the data to indicate that trials were more important than mission days in the evaluation of adaptation to task or work performance. It has been observed that by the second trial, whether performed on the same day or a week later, the time tended to approximate that obtained on the last preflight trial.

In summary, the time to perform a task on the second in-flight trial tended to approach the baseline time of the last preflight trial. For short missions, then, the early repetition of tasks critical for mission success would seem to be the most effective allocation of in-flight work activities.

Pattern of Task Performance

It was anticipated that some tasks would be done differently in the zero-g environment than under the one-g training conditions. In particular, it was expected that the pattern of in-flight work activity would differ from that exhibited in preflight training. For the present analysis, the basis for differentiating preflight from in-flight work patterns was the order in which the elements of a task were performed. The standard was the order determined by the checklist. Against this standard were compared the orders in which the elements were performed in-flight and in training. A measure of how closely these orderings corresponded to the standard was obtained by the Spearman Rank Difference Correlation Coefficient.

The following four tasks associated with experiment M092 were used in the analyses:

Prerun Subject	(15 element array)
Prerun Observer	(27 element array)
Postrun Subject	(15 element array)
Postrun Observer	(12 element array)

As an example of a typical array, the checklist ordering of elements in the Prerun Subject task follows:

1. Translate to Waste Management Compartment from Data Acquition Camera - Remote Control
2. Unstow harness and sponges
3. Clip harness to garment
4. Prepare vectorcardiograph harness
5. Don vectorcardiograph harness
6. Attach Body Temperature Measurement System cable to harness
7. Translate to Lower Body Negative Pressure Device from Waste Management Compartment
8. Open seal zipper fully
9. Adjust plates
10. Ingress Lower Body Negative Pressure Device
11. Mate vectorcardiograph to Subject Interface Box on Lower Body Negative Pressure Device
12. Close plates
13. Zip/adjust seal
14. Fasten/adjust seal belt
15. Don Blood Pressure Measurement System

Spearman correlation coefficients were computed for each trial of each crewman in his capacity as subject or observer. Since number of trials differed in-flight and in training, the number of coefficients for these conditions also differed.

Table IV presents the preflight and in-flight median correlation coefficients ("r") for the three Skylab missions. In general, the median preflight coefficients were larger than the in-flight coefficients for all three missions. The results indicated that the crewmen performed preflight tasks more in line with the checklist order than they did in-flight. The result made sense in that a crewman was more likely to follow instructions much more closely during training than after having mastered the task. Once mastery was achieved he could with more confidence experiment with better ways of doing the task. In addition, the crewman's weightlessness and the weightlessness of the masses he was handling made it more likely for his work pattern to change.

Another trend was also apparent in the data. Whereas the preflight coefficients remained relatively the same for each mission, the magnitude of the in-flight coefficients diminished steadily from the first to the last mission. This, too, was a reasonable result in view of the general transmission of information from one crew to another. In particular, any new and efficient methods of performing in-flight tasks were always transmitted to the crews of subsequent missions. Such methods would have very likely involved the ordering of elements comprising a task.

Despite the differences noted between the preflight and in-flight coefficients, both sets were of high magnitude. Coefficients of such magnitude indicated that the order in which the elements of a task were performed, preflight or in-flight, adhered relatively close to the order prescribed by the checklist.

TABLE IV. MEDIAN PREFLIGHT AND IN-FLIGHT SPEARMAN COEFFICIENTS FOR THE THREE SKYLAB MISSIONS

Skylab Mission	Preflight No.	Preflight Median "r"	In-flight No.	In-flight Median "r"
2	40	0.982	32	0.976
3	30	.978	43	.961
4	49	.982	53	.929

The Spearman coefficients were analyzed also in terms of the function the crewman performed, namely, whether as subject or as observer. Table V presents the median coefficients for these crewman roles, preflight and in-flight, for the three missions. The data indicated not only that the preflight-in-flight differences were consistent across the new subdivisions but that there was a strong trend for the Subject coefficients to be higher in magnitude than the Observer coefficients. These results flowed directly from the roles assumed by the crewmen. The subject, once in or attached to an instrument, was constrained by the sequential functioning of the mechanical system much more rigidly than was the observer whose options were more numerous because of his role in the experiment.

TABLE V. MEDIAN SPEARMAN COEFFICIENTS FOR SUBJECT AND OBSERVER, PREFLIGHT AND IN-FLIGHT FOR SKYLAB MISSIONS 2, 3, AND 4

Skylab Mission	Role	Preflight	In-flight
2	Subject	0.994	1.000
	Observer	0.952	0.935
3	Subject	.992	.988
	Observer	.968	.954
4	Subject	.982	.928
	Observer	.972	.938
Across all Missions	Subject	.991	.964
	Observer	.963	.943

In summary, then, the sequential pattern of a task as described in the checklist, was more rigidly adhered to in training than in-flight. Further, subject activity adhered to the checklist order more closely than observer activity because of the constraints of the instrumental system to which the subject was attached.

SUIT DONNING RESULTS

Suit donning is of vital concern to crew safety and operation during extravehicular activity. In addition, this activity (as well as suit doffing) has always been of interest to M151 investigators because it requires the full scope of the crewman's capabilities from fine motor dexterity, such as the precise alignment of connectors, to gross activities such as placing the helmet and gloves for later use. Crewman interaction is also involved, primarily during the zipper closures of the pressure garment assemblies. As the later crews studied the M151 films of the earlier crews, it was anticipated that significant changes in method from crew to crew would develop. Suit donning was nominally to be performed early, middle, and late in the mission on Skylab 3 and Skylab 4, thus providing some indication of zero-g adaptation.

The Skylab crewmen wore their suits for many different types of training in preparation for their respective missions. In most cases, they received assistance from suit technicians in donning and doffing the suits and as a result had a minimal number of training sessions where they actually simulated the donning and doffing procedures required for the Apollo telescope mount extravehicular activities. However,

from the exposure of having the suits custom fitted and from having the suits on for various exercises, the crewmen became familiar with the components required for extravehicular activity. During Skylab training, a maximum of only four extravehicular activity suit donning (and doffing) sessions were recorded by M151 for any crew. Table VI presents a summary of Skylab preflight training, with total time shown for 21 basic (and common) elements which must occur in the suit donning activity. The performance number refers to the crewman donning the suit.

Figure 5 presents the graphs of the averaged data in table VI. The outstanding characteristic of the three functions is the terminal point, the time for the last training session before flight. Whatever the differences in the initial training sessions, and these were large among the three crews, the final training performance required about the same amount of time (800-850 seconds) for the different crews. Although there was some inconsistency in the pairing of crewmen during the training sessions, it was felt that this had a minimal impact on the total times. There is certainly every indication that proficiency consistently improved.

Although all three crewmen donned the pressure garment assemblies prior to each extravehicular activity, only the two crewmen who would actually perform the extravehicular activity donned the necessary items specific to extravehicular activity. The third crewman did gain the additional experience of donning and doffing the basic part of the suit but did not participate to the extent of the two extravehicular activity crewmen. The performance number alluded to in this section refers to an assignment as extravehicular activity crewman.

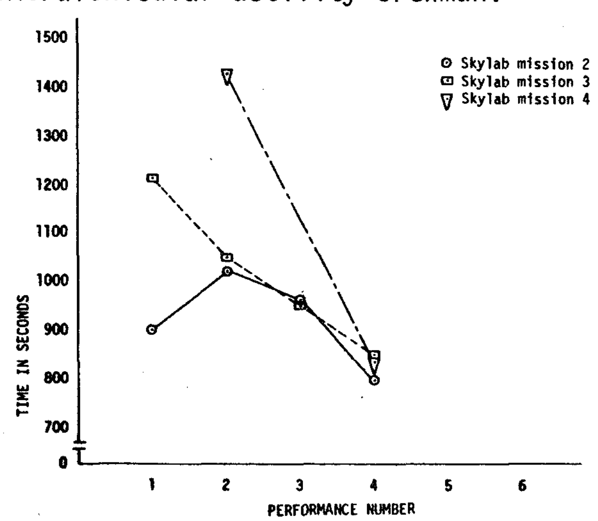

Figure 5. Preflight suit donning average time. (Sum of basic Elements)

TABLE VI. EVA SUIT DONNING TRAINING SUMMARY
(Sum of Basic Elements)

Skylab Mission	Perform. No.	Time to Launch (months)	Crewman	Assisting Crewman	(avg)	Time (Seconds)
2	1	9	CDR*	PLT†		763
	1	9	PLT	CDR		1043
					(avg)	903
	1	7	SPT‡	CDR		1231
	2	7	CDR	PLT		811
					(avg)	1021
	2	3	SPT	CDR		1061
	3	3	CDR	PLT		864
					(avg)	962
	3	1	SPT	CDR		874
	4	1	CDR	PLT		715
					(avg)	795
3	1	11	CDR	SPT		1334
	1	11	SPT	CDR		1089
					(avg)	1211
	1	8	PLT	CDR		912
	2	8	CDR	PLT		1159
	2	6	SPT	PLT		1072
					(avg)	1048
	3	6	CDR	PLT		1030
	3	6	PLT	CDR		879
					(avg)	955
	4	1.5	CDR	PLT		796
	4	1.5	PLT	CDR		914
					(avg)	855
4	1	5	SPT	CDR		N/A
	1	5	CDR	SPT		N/A
	2	4	SPT	PLT		1666
	1	4	PLT	SPT		1194
					(avg)	1430
	4	2	CDR	PLT		938
	4	2	PLT	CDR		730
					(avg)	834

Table VII and figure 6 which follow summarize the in-flight suit donning performances. Only one performance (on mission day 25) was filmed for Skylab 2, but it was the second time the Commander had donned his suit prior to extravehicular activity, while it was the first suit donning for the Pilot as an extravehicular activity crewman. An earlier extravehicular activity on mission day 14, involving the Commander and Scientist Pilot, was required on Skylab 2 during which the Pilot performed a non-extravehicular activity suit don. Three trials were recorded during each Skylab mission 3 and 4, but not always with the same pair of crewmen. The effect of total number of performances, difficultites (on Skylab 4) with the zipping operation because of snug-fitting suits, occasional intrusions of the non-extravehicular activity crewmember into the operation, and the small number of observations, created difficulties in identifying relationships between the timing (number of months or days, before launch) of training sessions and the timing of in-flight performances.

Large differences were found in the average times of extravehicular activity crewmen for the last performances: 669, 740, and 910 seconds respectively. These differences are probably due to factors other than the effect of training schedules, adaptation to zero gravity, learning, *et cetera*. Suit fit, for example, could have obvious effects on the time required to don the pressure garment assembly. This may be the reason that the Skylab 4 crewman took longer to don the pressure garment assembly late in the mission. In-flight anthropometric data* from Skylab 4 indicates that the heights of the crewmen significantly increased over the course of the mission and that the greater part of this increase was in the upper torso. This, then, would explain the much longer time required to zip the pressure garment assembly, a fact which M151 data disclosed. Correlation of the results of the antropometric findings and M151 were further substantiated by Skylab 4 crew comments in their postflight debriefings.

On Skylab 4 mission day 7, the Scientist Pilot and Pilot donned their suits (see table VII) with considerable difference in time required; 1192 seconds for the Scientist Pilot and 818 seconds for the Pilot. During this extravehicular activity preparation the Pilot seldom used the portable foot restraint while donning his own suit. He accomplished the suit donning in a free-floating mode or used his hands as a restraint system. Although it appeared difficult or awkward, the time was 31 percent less than that of the Scientist Pilot who remained in the foot restraint while donning his suit.

During the portion of the suit donning task where the crewmen assisted each other, the time taken by the "unrestrained" Pilot to zip the Scientist Pilot's pressure garment assembly zippers was 279 seconds,

*See Anthopometric Changes and Fluid Shifts by Dr. W. E. Thornton in volume II.

TABLE VII. EXTRAVEHICULAR ACTIVITY SUIT DONNING IN-FLIGHT SUMMARY
(Sum of Basic Elements)

Skylab 2

Perform. No.	Mission Day	Crew-man	Assist Crewman	Time (Seconds)
1	14	CDR*	SPT†	N/A
1	14	SPT	CDR	N/A
1	25	PLT	CDR	802
2	25	CDR	PLT	536
			(avg)	669

Skylab 3

Perform. No.	Mission Day	Crew-man	Assist Crewman	Time (Seconds)
1	10	SPT	PLT‡	1096
1	10	PLT	SPT	1094
			(avg)	1095
2	28	SPT	PLT	837
2	28	PLT	SPT	866
			(avg)	852
	57	SPT	CDR	740
	57	CDR	SPT	N/A

Skylab 4

Perform. No.	Mission Day	Crew-man	Assist Crewman	Time (Seconds)
1	7	SPT	PLT	1192
1	7	PLT	SPT	818
			(avg)	1005
2	40	PLT	CDR	N/A
1	40	CDR	PLT	N/A
2	44	CDR	SPT	1036
2	44	SPT	CDR	1057
			(avg)	1046
3	80	CDR	SPT	980
3	80	SPT	CDR	840
			(avg)	910

*CDR = Commander
†SPT = Scientist Pilot
‡PLT = Pilot

while the "foot-restrained" Scientist Pilot took only 222 seconds to zip the Pilot's zippers. In the first case the Pilot maneuvered around the Scientist Pilot, using the Scientist Pilot to restrain himself, as he performed the zipping operation. In the second case, the Scientist Pilot had the Pilot free-floating in front of him, and turned him as necessary to put the zipper in the best working position.

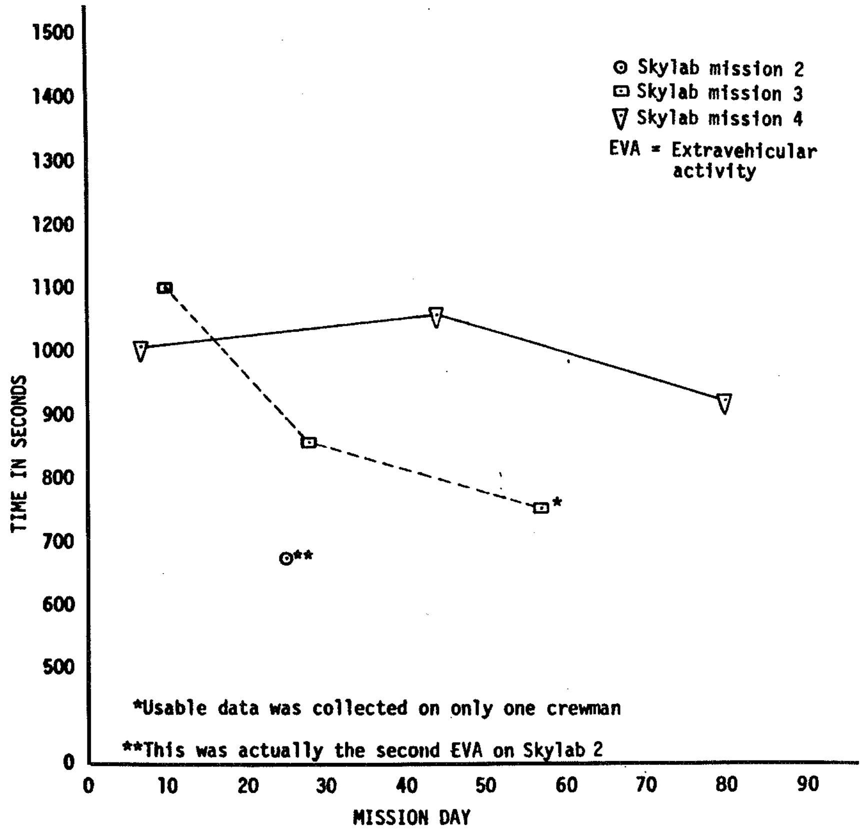

Figure 6. In-flight suit donning average time. (Sum of basic elements)

Although the Pilot took the shortest time for the total suit donning task, it would appear that in a two man operation, the "operator" should be restrained when working on a task that offers resistance such as a zipper; while restrained he is also in a better position to control the physical attitude of the subject.

FUNDAMENTAL TIME MEASURES

Camera Running Time and Basic Element Time

In addition to accurate time information, photographic methods also provided the basis for understanding why anomalous results could have been obtained. Two time measures based on photography were described in an earlier section - camera running time and basic element time. Although camera running time was the more complete measure, it also included the timing of activities not necessarily relevant to those being observed and measured. More limited in coverage, basic element time provided a measure for making valid comparisons between preflight and in-flight performance, between missions, and between crewmen.

Experiment M092 Prerun Subject data for the three missions were used to give a comparative picture of the two photographic measures. Figures 7 to 9 present the data for the three missions. The most readily observable characteristic of basic element time was its consistency and stability in contrast to the wide variations exhibited in camera running time. This may be observed most clearly in the respective graphs of the Skylab 2 Pilot (fig. 7), the Skylab 3 Pilot (fig. 8), and the preflight graph of the Skylab 4 Pilot (fig. 9). Despite the lower values obtained with the basic element time measure, it was a sensitive and realistic indicator of changes in the adaptation function. As an example of the value of basic element time, attention is directed to the two curves for the preflight performance of the Pilot on Skylab 3 (fig. 8). The upper curve, representing camera running time, would have indicated that performance became worse with practice. Basic element time, on the other hand, presented a more realistic picture of the adaptation function.

Both time measures, camera running time and basic element time, served important functions in the analyses of crewman task and work activities. Camera running time provided a basis for explaining unusual and unexpected results by isolating and identifying nonrelevant perturbations intruding on the efficient performance of a task. Basic element time served as the fundamental comparative measure and helped in identifying the nature of the differences in performance - in-flight and preflight, between missions, and between crewmen.

Voice/Telemetry as a Method of Data Acquistion

Because of film restrictions, it was not possible to photograph the totality of trials comprising each of the M151 experiments on the Skylab missions. A procedure was devised to sample those trials most critical to M151 objectives. The partial but carefully sampled data were used to generate the adaptation function which served as the basis for estimating data points not sampled by M151 film procedures.

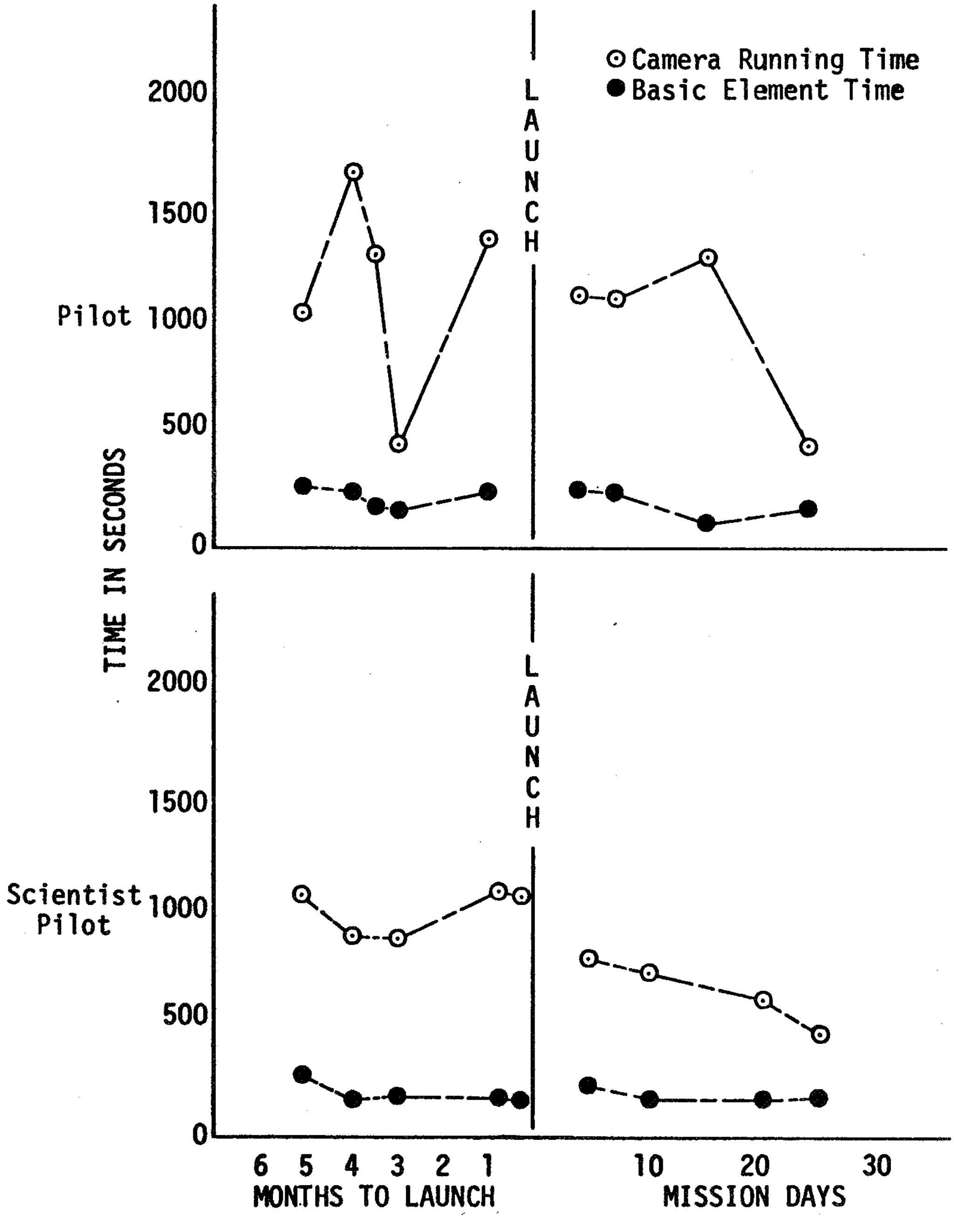

Figure 7. Experiment M092 prerun subject data (Skylab 2). Camera running time *vs.* basic element time.

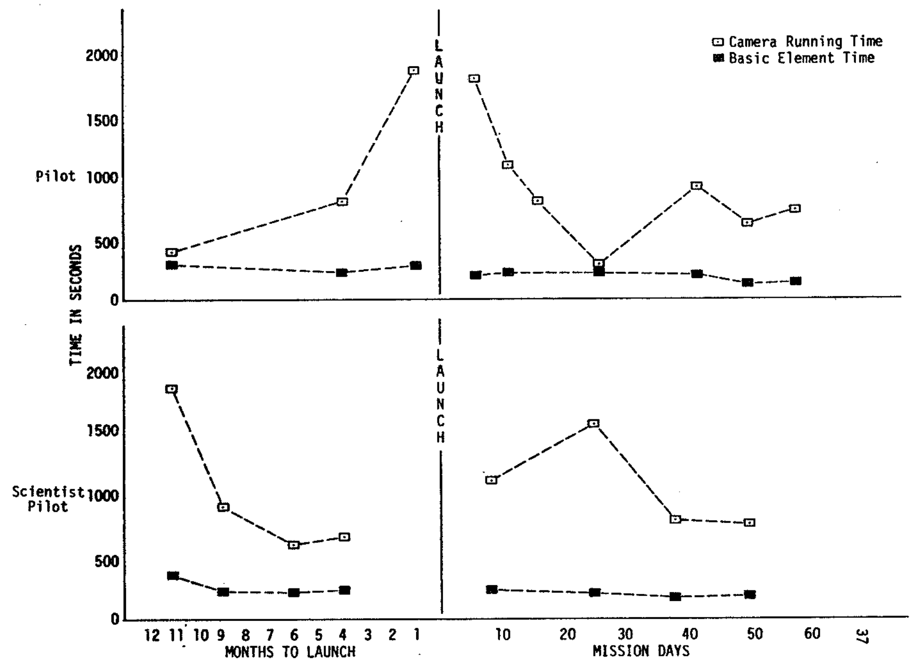

Figure 8. Experiment M092 prerun subject data (Skylab 3). Camera Running Time *vs.* Basic Element Time.

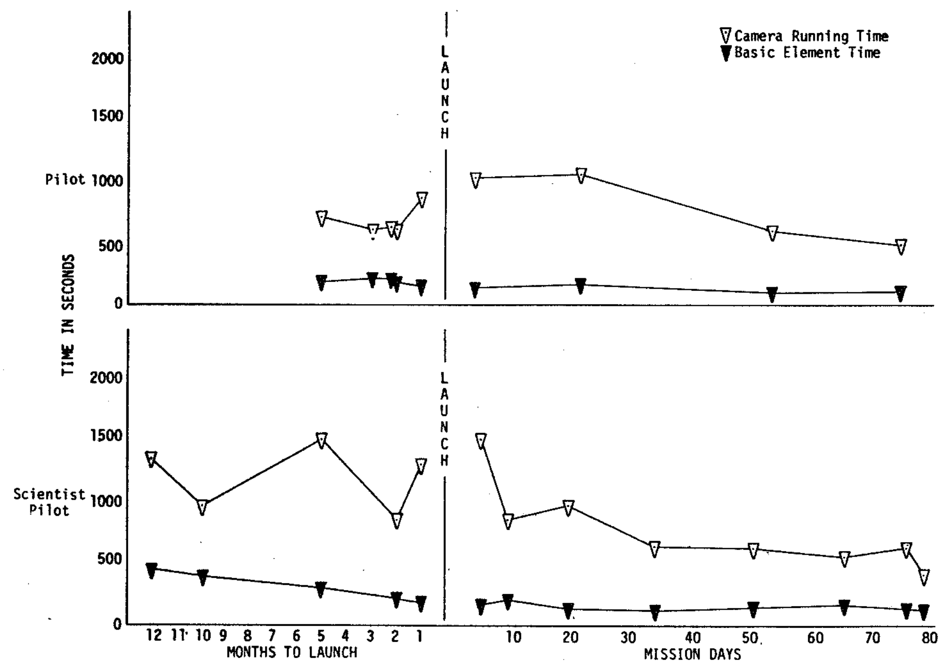

Figure 9. Experiment M092 prerun subject data (Skylab 4) Camera Running Time *vs.* Basic Element Time

Data for the complete set of trials would have been highly desirable; they were, however, unobtainable because of the limited amount of film available to M151.

The cooperation of the Skylab 4 crew was obtained to gather and report data on the performance of tasks done repeatedly and regularly over the entire 84-day mission. This involved the major medical experiments: M092, Lower Body Negative Pressure; M093, Vectorcardiogram; and M171, Metabolic Activity. These experiments were scheduled back-to-back in combinations of M092/M093 or M092/M171 and were performed within three or four day cycles with each crewman as subject. The result was that virtually every mission day from day 5 to day 83 had at least one of the combinations M092/M093 or M092/M171 as part of the daily flight plan. The only exceptions were the days the crewmen rested or performed extravehicular activity. Also twice during the mission, two major medical runs were made in the same day to free another day for multiple Earth Resource passes. Although subjects were scheduled on a regular basis, this was not the case for the observers. By the end of Skylab 4, the Commander was the observer for experiment M092 a total of 26 times, the Pilot a total of 23 times, and the Scientist Pilot only 18 times.

Performance time was obtained from the voice records and these indicated the points at which crewmen began or finished a task. In the course of the experiment, telemetry automatically recorded other events, such as calibrations, and these time points provided a check on possible discrepancies in the voice records.

No attempt was made to factor out anomalies or task interruptions present during the nominal run of the experiment. Interruptions caused by air-to-ground communications or other crewmen were considered, in the present analysis, as part of the total time required to perform the task. Other factors, however, not associated with the experiment proper, were eliminated from the tape-recorded time interval assigned to the experiment. These were the special tests which were introduced late in Skylab missions 3 or 4. They included Limb Blood Flow, Leg Blood Pressure, Facial Photos and Anthropometric Measurements to study body fluid shifts, venous compliance*, and changes in body size due to prolonged exposure to zero gravity†. In some tests, such as Limb Blood Flow, the time required could be factored out on the basis of telemetry associated with the test. In others, an estimate was determined from baseline data or from in-flight photos taken from M151

*Hemodynamic Studies of the Legs Under Weightlessness and Anthropometric Changes and Fluid Shifts by Dr. W. E. Thornton; see volume II.

†Biostereometric Analysis of Body Form by Dr. Michael Whittle; see volume I.

data. Early in Skylab 4, the special tests had significant impact on performance because the crew had little or no training on these tests prior to flight.

Accurate Voice/Telemetry data across the three Skylab missions were available in only one segment of the M092/M093/M171 complex of activities. The segment consisted of those activities following the completion of M092 data collection up to the point when M171 data acquisition was begun. In sequence, these activities included:

Time Count - Stop (End of M092)

Cuff/Inflate - Stop/Reset
Perform Hi-Calibration - (Hold 20-25 seconds)
System Select - Off
Tape Recorders - Off
Data Acquition Camera - On (If required)

Open Marmon Clamp and Lower Body Negative Pressure Device
Remove Legbands and Reference Adaptor from Subject
Close Lower Body Negative Pressure Device and Secure Marmon Clamp

Begin Metabolic Activity Calibration Check
Configure Experiment Support Systems for M171 Data
Electrode Impedance Check
Perform Hi-Calibration (Hold 20-25 seconds)
Vital Capacity Calibration (If required)
Vital Capacity Measurements (3 trials)

Time Count - Start (M171 Data Collection)

The time interval between the two time counts was used to compute averages for the three crewmen acting as observers in each of the Skylab missions. These data are presented in graphic form in figure 10. For two of the Skylab missions, 2 and 4, and partially for the third (Skylab 3) the graphs demonstrate the characteristic features of the adaptation function: high initial values and a progressive decrement over the course of the experiment.

The Skylab 2 graph was smoothest and most regular, uniformly lower than the others over the six trials, and decreasing at a relatively slow rate. Of the three graphs, it also suggested the most consistent performance.

The Skylab 4 graph, on the other hand, began at a much higher level and descended in a rapid but irregular manner over seven trials. A sharp

increase at the eighth trial reversed the trend momentarily. The rapid descent continued for the last three trials, of which the last two took substantially less time because the Skylab 4 crew had completed some of the required activity before the time period for which it was scheduled. The last two points, then, did not validly indicate the times for the corresponding trials.

The data from the Skylab 3 crew exhibited two radically different trends. For the first half of the mission, trials 1 through 5, the graph was a classic representation of the adaptation function. A sharp increase at trial 6 introduced a relatively stationary level of performance for the remainder of the mission, a level uniformly and substantially higher than that at which the other two crews were performing. The explanation of this anomalous segment of the graph is not readily apparent. Although it was well known that the M092/M093/M171 sequence of activities was not popular with the Skylab crewmen, the Skylab 3 crew were most direct and explicit in expressing their feelings. They felt it was boring, menial, and nonproductive of at least one person's time. It may well be that these feelings crystallized midway during the mission with a correlative loss of motivation and a consequent loss of efficiency.

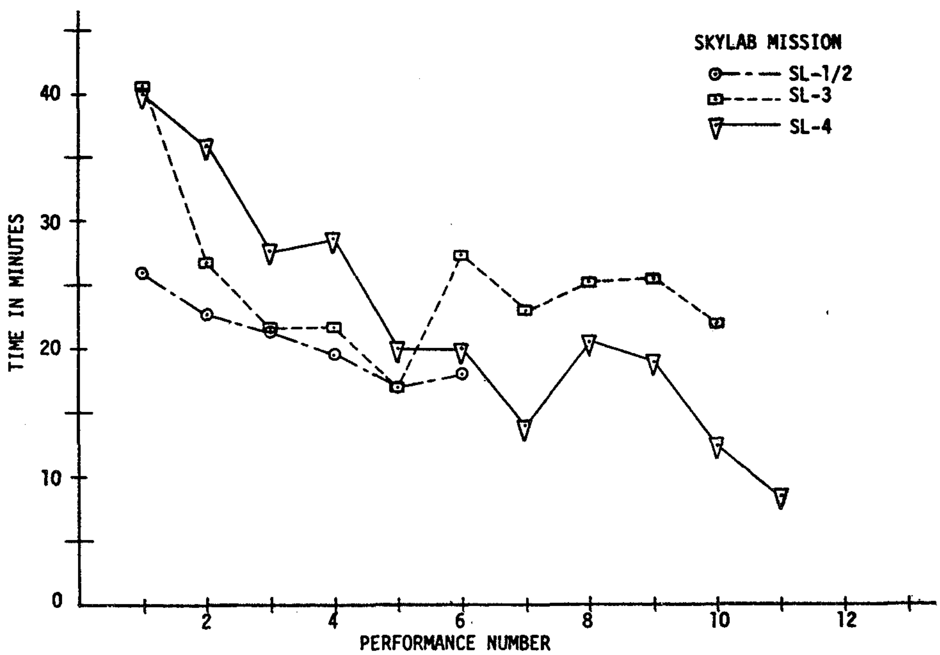

Figure 10. Experiment M092 end to M171 start.
(Observer activity - 3 crewman average).

In summary, Voice/Telemetry data were a valuable adjunct in the evaluation of task performance. When the tasks were done in a nominal manner, Voice/Telemetry gave a valid estimate of the actual time expended during the performance of the task. The drawback in using Voice/Telemetry was that the measure also included everything else that happened within that time period even though it may have had no definite relation to the task at hand. Voice/Telemetry data also failed to correct for such unusual situations as demonstrated in the last two performance trials of the Skylab 4 crew.

PERFORMANCE LATE IN MISSION

An important objective of experiment M151 was to examine the performance late in the mission for signs of anomalous performance due to the long exposure in the Skylab environment. In terms of the adaptation function an anomalous result would be either a significant increase in time to perform tasks or a significant increase in variability towards the latter part of the mission.

To determine whether these two effects were operating on the Skylab 4 mission, the voice/telemetry data for M092, M171, and M093 were divided into thirds; the initial third, the middle third, and the final third of the Skylab 4 mission. These data, in the form of means and standard deviations, are presented in table VIII.

As the data in the table indicate, the means for the initial, middle, and final portions of the mission decreased steadily for the three experiments. The standard deviations decreased sharply from the initial third to the middle third and became stabilized at about this period of the mission. The slight increases in standard deviation from the middle to final third for experiments M092 and M171 could be considered as random variations about a relatively stable level. Some substantiation for this conclusion can be found in the standard deviations observed in experiment M093 where there was a decrement from the middle to the final third.

TABLE VIII. MEANS AND STANDARD DEVIATIONS OF TASK PERFORMANCE FOR THE INITIAL, MIDDLE, AND FINAL THIRDS OF THE SKYLAB 4 MISSION

Experiment	Initial Third		Middle Third		Final Third	
	$\bar{X}$	S.D.	$\bar{X}$	S.D.	$\bar{X}$	S.D.
M092	34.7$^{\alpha}$	6.3	27.2	2.8	23.3	3.1
M171	30.2	5.4	19.0	2.4	15.9	2.9
M093	14.9	2.9	10.7	1.6	9.7	1.2

$^{\alpha}$in minutes

In summary, then, there was no significant evidence for deterioration of performance on Skylab 4 as the mission approached its culmination. As a matter of fact, performance continued to improve while variability did not increase significantly during the final third of the Skylab 4 mission.

CONCLUSIONS

The fundamental results from the above analyses can be summarized in several brief conclusions.

- Despite pronounced variability in training schedules and in initial reaction to the Skylab environment, in-flight task performance was relatively equivalent among the three Skylab crews.

- Behavioral performance continued to improve from beginning to end of all Skylab missions.

- There was no evidence of performance deterioration that could be attributed to the effects of long-duration exposure to the Skylab environment.

- The first in-flight performance of a task generally took a longer period of time than the last preflight performance. The longer performance time could be the result of a number of factors - stress of last-minute flight preparations, change to zero-g Skylab environment, greater care and caution in the performance of in-flight tasks, an experience of work overload during the early period of the mission.

- Performance adaptation was very rapid. By the end of the second performance trial, about 50 percent of all task elements were completed within the time observed for the last preflight trial.

- The pattern of work performance changed more in-flight than it did during preflight performance.

- Three fundamental time measures, *i.e.*, Basic Element Time, Camera Running Time, and Voice/Telemetry Time, were shown to have specific application in situations relevant to their use.

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CREW EFFICIENCY ON FIRST EXPOSURE TO ZERO-GRAVITY

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ABSTRACT

The many individual work tasks accomplished by each of the three Skylab flight crews in their early activation phase have been identified and their respective performance times estimated. These work performances were compared both with preflight estimates of the rate at which work would be done and with crew output later in the mission when adaptation was complete and when the crewmembers were experienced in zero-gravity operations. The very substantial amount of work devoted to repair tasks during the early mission days was also included.

It was found that on only two of the total of nine full or partial activation days was the crew work output significantly reduced. On the day of lowest efficiency, mission day 2 of the Skylab 3 mission, it appears that the crewmen were working at approximately 75 percent of their "normal" efficiency and may have lost approximately 7 man-hours of work. Overall, a nearly constant level of work was achieved on these activation days. However, as crew proficiency improved later in the missions, the daily crew work output in these same categories increased from approximately a 26 man-hour/day to at least a 34 man-hour/day.

INTRODUCTION

Soon after reaching orbit several crewmembers of both Apollo and Skylab flights (as well as Russian cosmonauts) have reported symptoms of malaise or stomach discomfort, occasionally reaching the point of vomiting. While these symptoms have always disappeared after a few days, they have generated some concern about the ability of crewmen to work efficiently in the first few days of a space mission. This is a particularly important consideration for Shuttle operations, since many flights will probably be limited to about seven days in orbit, until a sufficient number of Orbiters are available to allow longer periods in space.

METHODS AND DATA

Skylab data may allow a reasonably objective analysis of crew efficiency to be made during the first few days in flight since an "activation" schedule was prepared preflight for each crew. A rather close accounting was made to the ground controllers as the activaton tasks were completed, as well as an accounting of any additional work accomplished that had not been scheduled preflight. Part of the concern about crew efficiency has arisen because some of the scheduled activation tasks were delayed; in addition, it is essential to consider the *added* tasks required, usually of a "trouble shooting" nature, before the true picture of efficiency can be evaluated. The basic data reported here has been collected by G. Doerre, J. Arbet, and S. Graham from the records of each of three Skylab missions as it was flown (1). As Doerre was also responsible for the "activation" phase crew training prior to launch, he and his associates are most familiar with the individual tasks that are listed below.

Perhaps the most useful portion of their data for this study is the tabulation of "activation tasks accomplished" on each of the first few days after rendezvous with the Skylab for each of the three crews. These tables list individual tasks completed by each of the three crewmembers, with the time investment estimated to the nearest five minutes. These estimates are based on the time it took for a trained crewman to perform each task in preflight training at Johnson Space Center. Although not exact, it has been the general concensus of crewmembers that the times allotted are reasonable. The tasks listed are intended to include all the useful work accomplished, *excluding* food preparation, eating, sleeping, rest periods, personal hygiene and housekeeping activities. As an example of the depth of detail, the table for Skylab 3 (the second manned mission) is attached as appendix A.

The total time accumulated each day in "activation tasks accomplished" divided by the number of "man-hours available" for work will be defined as the efficiency ratio, E.R. The "man-hours available" is simply a measure of the total crew time awake during the activation phase of each flight. If every waking moment was spent on activation tasks or repairs, this ratio would be unity. However, since the many essential tasks of food preparation, eating, sleeping, personal hygiene and houskeeping are excluded, the efficiency ratio will obviously be less than one. In fact, if we consider a normal day here on Earth to contain 16 hours awake, split evenly between useful work (8 hours) and other "overhead" or housekeeping functions, this day would have an efficiency ratio of 0.5 by our definition. Justification for this definition of E.R. will be provided a little later. Table 1 shows

the activation man-hours accomplished for each crew on each applicable mission day, through mission day 4, and also the number of man-hours available on each day. From these data the efficiency ratio may be obtained, as is shown in table I and figure 1.

Some explanation of the table entries is required. The first mission crew (Skylab 2) had a larger activation task than succeeding missions; they were scheduled for three full days of activation, starting on mission day 2. The next two crews were scheduled only for about 2.5 days each. For the second crew (Skylab 3), the activities were begun on mission day one, after launch and rendezvous were completed. The third crew remained in the command module on mission day one and were scheduled to begin activation on mission day 2. Therefore, only half-days are shown under man-hours available for Skylab 3 on mission day 1 and Skylab 4 on mission day 4. A somewhat abbreviated activation day was also scheduled preflight for Skylab 3 on missions day 3. The entries under man-hours accomplished were, of course, accumulated only in these available hours.

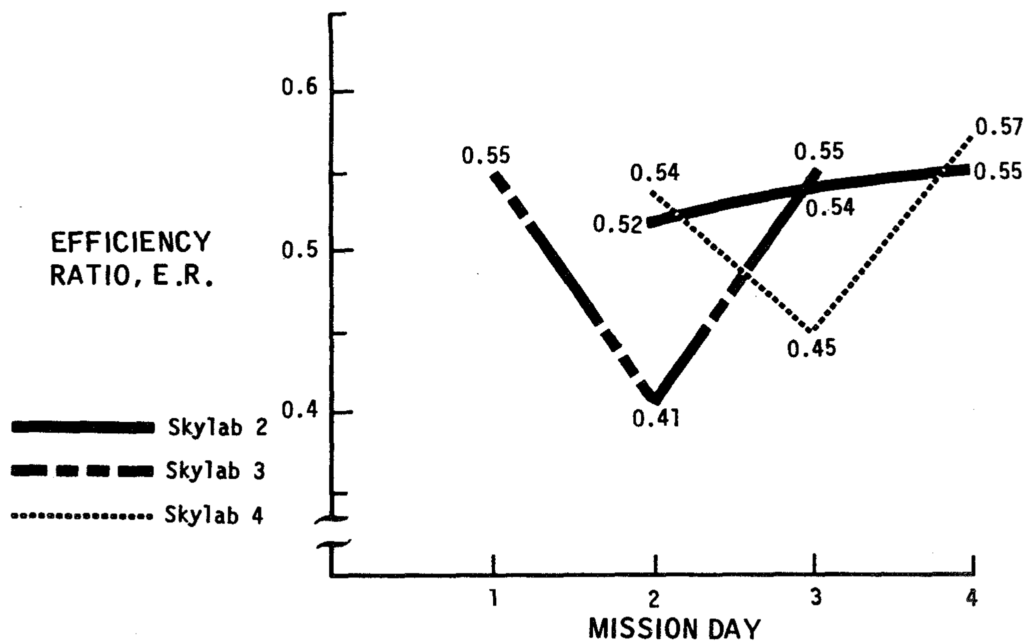
From these data it may be seen that on seven of the nine activation days, the efficiency ratio average was just over 0.54. Only on mission day 2 of Skylab 3 and mission day 3 of Skylab 4 did it drop significantly below this value. Mission day 2 of Skylab 3 was the day in which this crew felt most handicapped by motion sickness. On this day there was an attempt to provide the crew with about two hours of rest in midday, although they were required almost immediately to respond to a Master Alarm indication of low bus voltage. Much of the scheduled rest period was then spent in tracking down the source of the large power drain. (It was a short in an experiment carried in the Command-Service Module.)

The Skylab 3 crew had been awake on mission day 1 for a total time of 22 hours (only 7.5 available for activation), followed by 18 waking hours on mission day 2. These long days may well have contributed to reduced efficiency on mission day 2, as well as the motion sensitivity. Assuming that an E.R. $\approx$0.54 is "normal", we estimate from table I that the time lost due to reduced efficiency is approximately (0.54 - 0.41) 54$\approx$7.0 man-hours. Similarly, the Skylab 4 crew on mission day 3 may have lost about (0.54 - 0.45) 52.5$\approx$4.7 man-hours, at least some of which was due to motion sensitivity.

TABLE I. ACTIVATION MAN-HOURS: ACCOMPLISHED AND AVAILABLE

	MISSION DAY 1			MISSION DAY 2		
Skylab Mission	Accomplished	Available	Efficiency Ratio	Accomplished	Available	Efficiency Ratio
2				24.4	46.5	0.52
3	12.3	22.5	0.55	22.0	54.0	0.41
4				27.5	51.0	0.54

	MISSION DAY 3			MISSION DAY 4		
Skylab Mission	Accomplished	Available	Efficiency Ratio	Accomplished	Available	Efficiency Ratio
2	27.7	51.0	0.54	26.3	48.0	0.55
3	22.3	40.5	0.55			
4	23.8	52.5	0.45	10.3	18.0	0.57



Efficiency Ratio (E.R.), defined as the ratio of activation tasks accomplished to the number of man-hours available during the activation phase of each Skylab flight. The text describes these quantities in more detail and justifies the exclusion of the many "overhead", yet essential, tasks of food preparation, eating, sleeping, rest, personal hygiene and housekeeping.

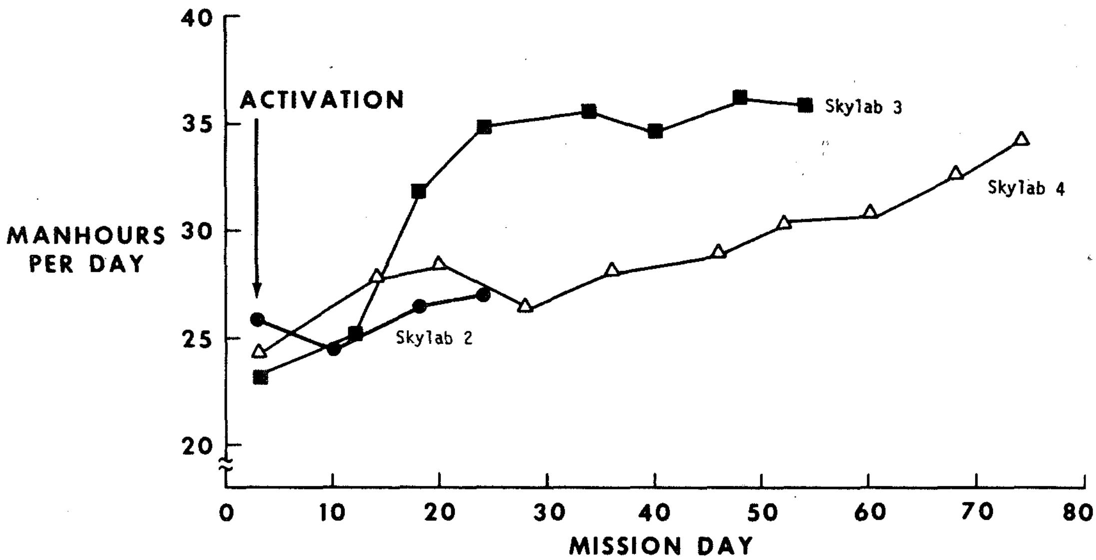
Figure 1. Efficiency ratio.

Crew performance early in the flight can be viewed from still another aspect. We may ask "how many man-hours of activation tasks remained incomplete at the end of the scheduled activation interval"? For the three crews respectively, the answers are 0.1, 13.5, and 4.8 man-hours. For all three flights, essentially all of these remaining tasks were completed by the end of mission day 4. Although 13.5 man-hours of activation tasks remained to be accomplished at the end of mission day 3 on Skylab 3, additional repair tasks of 12.9 man-hours had been completed. The Skylab 4 crew completed an extra 4.2 man-hours of added tasks in their activation phase. These results indicate that all three crews were able to deliver, in the first three or four days of their respective flights, rather close to the amount of work they had been scheduled preflight, to accomplish. We will see later that flight planning had been somewhat conservative by late mission standards, but was apparently quite realistic for these first few days.

It may not be clear why the rather large number of essential "overhead" tasks (food preparation, eating, sleep, rest, personal hygiene and housekeeping) have been excluded in computing an efficiency ratio. There are two principal reasons. First, we have just seen that all three crews were working at very close to the preplanned rate during these first few days. To have included these "overhead" tasks in computing an efficiency ratio would simply have resulted in a value very near unity and we would not have been able to see later shift from less "overhead" work into a greater percentage of productive activity. Second, we have selected only activation and repair tasks which can be compared directly to experiment and related operations later in the flight. In this way, we can see most clearly the number of man-hours it is reasonable to expect a crew to deliver both early and late in a mission for activation and payload operational tasks.

We should now turn to the comparison of productive work accomplished in the first few days of flight with that accomplished later on when adaptation was complete and the routine well established. In addition to the direct performance of experiment operations, there are several other "operational tasks" which should be included before the amount of work produced later in the mission can be compared with work output in the activation phase. These operational tasks include physical exercise, some "post-sleep" activities related to experiments, television, photography, and repairs. When these tasks are added to the specific experiment operations, the Skylab 3 crew delivered over 31 man-hours of productive work per day, and increased this to about 36 man-hours per day toward the end of the mission, which would correspond to and E.R. = 0.75 as defined before. These are the numbers most directly comparable to a "normally" efficient activation day of about (0.54 x 48 man-hours awake) ≈26 man-hours/day of work accomplished (2, 3, 4).

Figure 2 shows the trend of productive work rate for all three crews from activation phase through the completion of their experiment operation. Each point shown is an average of three to seven days work, with days of "rest" or extravehicular activities excluded.



The tasks included in productive work consist not only of direct experiment performance, but also experiment related activities of physical exercise, photography, television, science demonstrations and repairs. These totals may be compared with the activation and repair work rate early in the mission and are representative of the amounts of work available to experimenters. Each point shown is an average of from three to seven days activity and excludes days of "rest" or extravehicular activity preparation and performance.

Figure 2. Productive work rate *vs.* Mission Day.

SUMMARY

Summarizing all these results, we have found that all three of the three-man Skylab crews accomplished activation work at an efficiency ratio of about 0.54, equivalent to 26 man-hours/day, assuming they were all awake for 16 hours and asleep for eight hours each day. On one of the nine total days spent all or partially in activation, mission day 2 of Skylab 3, the crew efficiency dropped about 25 percent. (E.R. = 0.41), attributable largely to transient motion sickness. After experiment operations began, the Skylab 3 crew soon accomplished similar work tasks at a rate in excess of 31 man-hours/day, increasing to about 36 man-hours/day toward the end of the mission (2). The Skylab 4 crew accomplished work in these same categories at a rate of

about 28 man-hours/day early to above 33 man-hours/day late in their mission (3).

We believe the improvement in productivity has come about for two reasons,

- ° greater training and proficiency in experiment operations as compared to activation tasks, and
- ° improved efficiency as experience is gained living in zero-gravity.

The activation tasks were to be performed only once by each crew and consisted of many largely unrelated activities. Each crew had the opportunity to practice the full procedures in their trainers at Johnson Space Center only a few times prior to launch. However, training for experiments and especially those consuming the most time (solar, medical, Earth resources) was very thorough and extensive. Still, operations in zero-gravity could not be precisely simulated preflight, and a further training improvement was noticed during the course of the mission. More time became available to experiments because the time required for the "overhead" tasks of food preparation, eating, housekeeping, *et cetera* was reduced as experience was achieved in the routine of zero-gravity living.

CONCLUSIONS

It appears that a relatively modest amount of crew time may have been lost due to motion sickness on Skylab missions 3 and 4 but that each crew's performance was never substantially impaired for more than one day.

During the three activation intervals, less than 12 man-hours were lost to reduced efficiency (including the effects of motion sensitivity) while almost 200 man-hours of productive work were delivered.

A very substantial improvement in work rate is found, however, for tasks in which simulation and training time was extensive and for tasks of a repetitive nature which allowed zero-gravity operations to be optimized.

REFERENCES

1. Skylab Activation "As Flown" data, prepared by G. Doerre, J. Arbet and S. Graham, April 30, 1974.

2. Final Skylab FAO Daily Status Report, Skylab 3 Mission, September 25 1973.

3. Skylab FAO End of Mission Status Report, Skylab 4 Mission, February 15, 1974.

4. Final Skylab 2 Flight Plan Data, July 5, 1973.

APPENDIX A

SKYLAB 3 ACTIVATION TASKS ACCOMPLISHED

NOTE: The time listed for each task is the requirement estimated for a trained crewmen based on preflight simulations. It is not the actual time consumed in-flight, which could be longer. Crewmen abbreviations are CDR/SPT/PLT for Commander, Scientist-Pilot and Pilot. Tasks added to the preflight schedule, usually troubleshooting, are identified with preceding asterisk.

I. Mission Day 1 (1930-0300 UT = 7.5 hr, for activation tasks)

	TASK	CREWMAN	TIME (MAN-MIN)
1.	CM/MDA Tunnel Pressure Integrity Check	CDR/SPT	10
2.	Sec. Glycol Evaporator Dryout	PLT	5
3.	Bat. A Charge	PLT	5
4.	Tunnel Hatch Removal	CDR/SPT	60
5.	Docking Latch Verification	CDR/SPT	--
6.	Probe Removal	CDR/SPT	--
7.	Drogue Removal	CDR/SPT	--
8.	Pri. Glycol Evaporator Dryout	CDR	5
9.	Command Module Suit Circuit Deact.	CDR	10
10.	Drogue & Probe Stowage	CDR/SPT	20
11.	Air Duct Installation	CDR/SPT	20
*12.	General Clean Up of CSM	CDR/SPT	50
13.	Pri. Glycol Dryout Termination	CDR	5
14.	Glycol Circuit Reconfiguration	CDR	5
15.	Update	CDR	--
16.	Umbilical Connection Preparation	CDR/SPT	10
17.	CM O_2 System Configuration	CDR	10
18.	CSM/SWS Basic Communication Configuration	CDR	10
19.	Center Couch Stowage	CDR	15
20.	Sextant P52 (Option Sextant 3)	CDR	10
21.	GDC Align	CDR	--
22.	S190A Window Protector Installation	SPT	10
23.	Observe Pilot Operations	SPT	10
24.	CSM/MDA Umbilical Connection	SPT	10
25.	Caution & Warning Activation	SPT	10
26.	Airlock Ground Disconnection	SPT	5
27.	Communications Activation Check	SPT	5
28.	Mission Timer Update	PLT	5
29.	Sec. Glycol Dryout Termination	PLT	5
30.	MDA Hatch Opening	SPT/PLT	15
31.	MDA Light Turn On	SPT/PLT	10
32.	CSM RCS Propellant Reconfiguration	PLT	5
33.	MDA/STS Entry	PLT	20
34.	STS Circuit Breaker Panel Configuration	PLT	15

I. MISSION DAY 1 (CONT)

	TASK	CREWMAN	TIME(MAN-MIN)
35.	STS Panel Configuration	PLT	5
36.	S190 Window Heater Activation	PLT	5
37.	Video Tape Recorder Activation	PLT	--
38.	02/N2 Activation	PLT	5
39.	Oxygen Mask & Supply Configuration	PLT	20
40.	AM/Dome Entry	PLT	5
41.	OWS Fan Activation	PLT	5
42.	OWS Switch Configuration	PLT	15
43.	Thermal Control System Activation	PLT	5
44.	CSM Caution & Warning Check	CDR	10
45.	SWS Caution & Warning Checkout	CDR/SPT	45
46.	CM Stowage Reconfiguration	CDR/SPT	30
47.	Evening Status Report	CDR	10
48.	Assist CDR with CSM Caution & Warning Check	SPT	5
49.	Fire Sensor Check	SPT	15
50.	Urine/Fecal Collector Activation	SPT	45
51.	Fecal Processing	SPT	30
52.	Water System Gas Bleed	PLT	10
53.	Pressure Suit Transfer/Drying	PLT	30
54.	Bed. 1 Bakeout Initiate	PLT	5
55.	Bat. B Charge	CDR	5
56.	Sleep Compartment Activation	SPT/PLT	55
57.	Bed. 1 Temperature Verification	PLT	5

TOTAL MAN-MIN. = 740
TOTAL MAN-HOURS = 12. 3

II. MISSION DAY 2 (1100-0500 UT = 18 hr)

	TASK	CREWMAN	TIME (MAN-MIN)
1.	Post Sleep Activities	ALL	90
2.	Battery A Charge	CDR	5
3.	Sextant P52 (Option 3)	CDR	10
4.	Medical Resupply Canister Transfer	CDR	20
5.	Report N23 & N93	CDR	--
6.	H20 Separator Plate Wetting Preparation	CDR	15
7.	ATM Controls & Displays Coolant Loop Activation	SPT	5
8.	ATM Console Activation	SPT	45
9.	Bed. 2 Bakeout Initiation	PLT	5
10.	Bed. 2 Temperature Verification	PLT	5
11.	Water Sample	PLT	25
12.	Water System Activation	PLT	30
*13.	Trouble Shooting H20 Dump Pressure Indicator	PLT	10
14.	Stowage Reconfiguration	CDR	180
15.	P50-IMU/ATM Orientation Determination	CDR	25
16.	P52 IMU Realign	CDR	--
17.	E-Mod	CDR	5
*18.	Battery-Regulator #3 Trouble Shooting	SPT	20
19.	Assist CDR with P50 & P52	SPT	25
20.	CM Urine/LiOH/Fecal Bag Transfer	SPT	15
21.	Urine Collection System Sampling	SPT	105
22.	Wardroom Water System Activation	PLT	40
23.	Potable Water Chlorination	PLT	15
24.	CSM Navigation Power Down	CDR	10
25.	CM Condensate Blanket Installation	CDR	5
26.	CM Evaporator Reconfiguration	CDR	5
27.	Entry Bat. Isolation	CDR	5
28.	Suit Drying (2nd. Suit)	CDR	20
29.	CSM Quiescent Panel Configuration	CDR	60
30.	Wardroom Window Activation	SPT	20
31.	100 PPM Drain & Flush	PLT	15
32.	Trash Bag Installation	PLT	15
33.	Bed. 2 Bakeout Termination	PLT	5
*34.	S071/72 Trouble Shooting	PLT	80
*35.	CM Waste H20 Dump to OWS	CDR	20
36.	H20 Separator Plate Servicing	CDR	50
37.	CM Food Transfer	SPT	60
38.	H20 System Flush	PLT	10
39.	Wardroom H20 System Bleed	PLT	50
40.	Condensate System Activation	CDR	10
41.	Molecular Seive A Activation	CDR	10
42.	Flight Data File Transfer Update	CDR	60
43.	Evening Status Report	CDR	10
44.	Experiments Transfer/Preparation	SPT	80
*45.	02 Fuel Cell Purge	CDR	5
46.	Suit Drying (3rd Suit)	CDR	20
		TOTAL MAN-MIN =	1320
		TOTAL MAN-HOURS =	22.0

III. MISSION DAY 3 (1400-0300 =13 hr)

	TASK	CREWMAN	TIME(MAN-MIN)
1.	Post Sleep with M110	ALL	330
2.	Flight Data File	CDR	20
3.	Suit Drying Termination	CDR	15
*4.	Condensate System Trouble Shooting	CDR	390
*5.	Condensate System Trouble Shooting	PLT	60
*6.	Lighting Assembly Trouble Shooting	CDR	5
7.	Weigh Food Residue	SPT	30
8.	Body Mass Measuring Device Calibration	SPT	70
9.	Return Water Container Fill/Transfer	PLT	30
*10.	Urine Separator Trouble Shooting	SPT	45
11.	Transfer Return Clothing to Command Module	PLT	10
12.	Command Module Stowage Transfer	PLT	30
13.	Film Transfer	SPT/PLT	90
14.	PP02 Sensor Replacement	CDR	25
15.	Squeezer Bag Dump	CDR	10
16.	Sample Mass Measuring Device Transfer and Calibration	SPT/PLT	90
*17.	Trash Airlock Leak Trouble/Shooting	ALL	90
		TOTAL MAN-MIN =	1340
		TOTAL MAN-HOURS =	22. 3

MUSCULOSKELETAL CHANGES

MINERAL AND NITROGEN METABOLIC STUDIES, EXPERIMENT M071

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Michael W. Whittle, M.Sc., M.B., B.S.*[‡]*; Malcolm C. Smith, D.V.M.*[‡]
Jeanne Reid; Carolyn Leach, Ph.D.*[‡]*; Connie Rae Stadler*[§]*;
and Deanna D. Sanford*[§]

ABSTRACT

Metabolic study of the effects of space flight on various chemical elements, particularly those with special relevance to the musculoskeletal system, was performed on the nine astronauts who participated in the three Skylab flights of 28, 59, and 84 days, respectively, during 1973 and 1974. The study required of the cooperating crewmen quite constant dietary intake, continuous 24-hour urine collections, and total fecal collections for 21 to 31 days before each flight, throughout each flight, and for 17 to 18 days after each flight for a total of 909 man-days of metabolic study. Results of similar but much earlier metabolic studies of bed rest had indicated that weightlessness of space flight would cause derangements in musculoskeletal metabolism, but the only previous controlled measurements in space were made on the 14-day Gemini VII flight in 1965.

In the Skylab "experiment", increases in urinary calcium during space flight and in-flight changes in calcium balance were closely similar in degree to those found in bedrest immobilization. The similarity to bed rest in the pattern of urinary calcium increases and of total calcium shifts suggested that calcium losses would continue for a very long time. Significant losses on nitrogen and phosphorus occurred that were associated with observed reduction in muscle tissue. Both mineral and muscle losses occurred despite vigorous exercise regimens during flight. It was concluded that these studies give warning that capable musculoskeletal function may be significantly impaired during prolonged space flights lasting one and one-half to three years unless protective measures are developed.

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INTRODUCTION

Experiment M071 was an effort to use a relatively precise but arduous technique of study of human metabolic (or chemical) processess - called "Metabolic Balance Study" - to determine major changes in chemical state of the muscular and skeletal systems. This technique is difficult to use correctly even under near-ideal clinical research center conditions, but in Skylab it had to be applied under the peculiar and very limiting conditions of space flight and of the preparation for and recovery from it. The metabolic balance technique requires extraordinarily meticulous attention to detail in dietary intake and collection of excreta hour-by-hour. In Skylab this was possible only because of the dedicated cooperation throughout of dietitians, dietetic staff, specimen collection staff, laboratory staff, NASA management staff at all levels and particularly of the participants - the astronaut crews. The advantage of the balance technique, when properly carried out, is the precision with which changes in body elements in milligram quantities can be measured and the ability with which patterns of almost day-by-day chemical change can be described. No metabolic study was ever perfect and this one, we must say, lived up to that tradition; but the study was clearly successful *enough* to provide definite conclusions and to permit sensible interpretations of significance for the future.

Prediction that the various stresses of space flight, particularly weightlessness, would bring about significant derangements in the metabolism of the musculoskeletal system had been based on various mineral and nitrogen balance study observations of normal healthy subjects at long immobilized or inactive bedrest. The earliest was that of Deitrick, Whedon and Shorr (1) in 1948, the calcium balance results of which are graphed here in figure 1.

Immobilization of four healthy young men in body casts for six to seven weeks led to marked increases in urinary calcium and significantly negative calcium balances, and there were related losses of nitrogen and phosphorus. Several subsequent bedrest studies of normal subjects confirmed these substantial metabolic derangements (2). The longest observation (Donaldson, Hulley and associates, 1970)(3) showed that although the elevated urinary calcium subsided partially during the third and fourth months of bedrest, it nevertheless remained significantly higher than control levels for as long as bedrest was continued (for 7 months) and, furthermore, did not fall to normal until the subjects were put back on their feet.

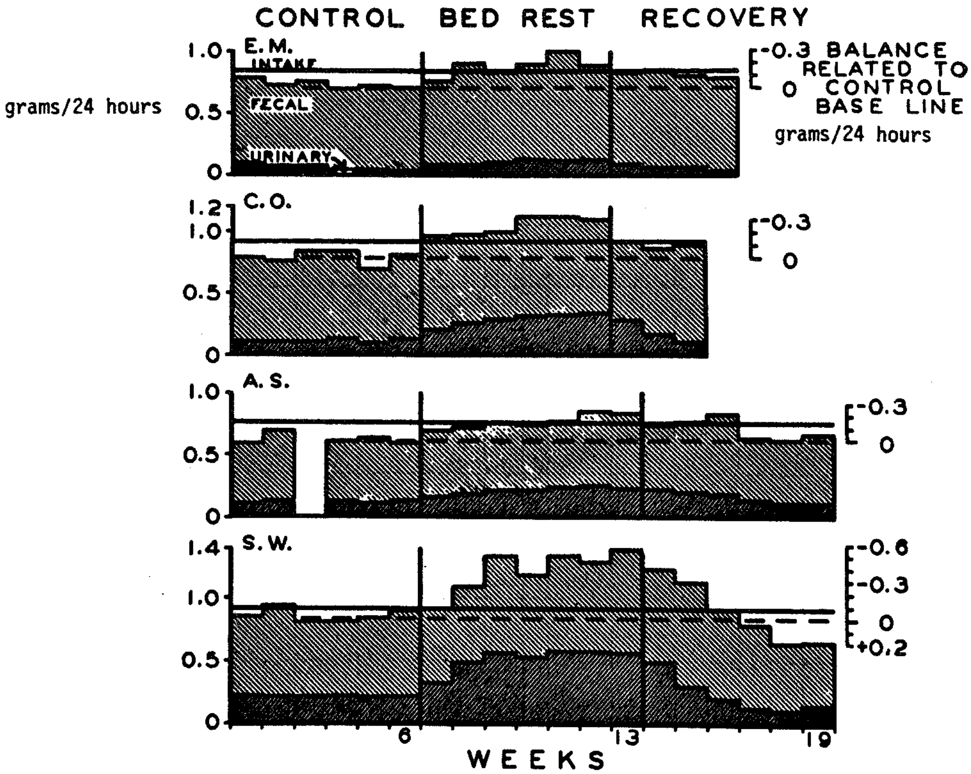


Figure 1. Effect of immobilization on the calcium metabolism of four normal male subjects. In each subject the daily calcium intake was kept constant throughout all periods of the experiment. For each subject the control baseline (interrupted horizontal line) is an average of the total outputs of the last four control weeks. In this graph the intake and output are both plotted upward from the zero baseline. (Reproduced by permission of Medical Clinics of North America, 35, No. 2: 545, March 1951.)

The only attempt at controlled metabolic observations in space flight prior to Skylab was performed by us (4) in conjunction with the 14-day Gemini VII flight in 1965. That relatively short study revealed quite modest losses of calcium and phosphorus and varied changes in the metabolism of other elements.

PROCEDURE

A cardinal principle of metabolic study is that changes in the excretion of key nutrient elements, such as calcium or nitrogen, can only be interpreted as due to the influence or agent under test if environmental factors are kept *as constant as possible* from phase-to-phase and from day-to-day. One of the most important of these environmental

factors in metabolic study is the dietary intake. The dietary intake in the M071 study was dependent upon the selection, for various reasons of stability and acceptability, of some 70-odd space food items by NASA food technologists. Selection was constrained for most items by the requirements of stability at room temperature in space for more than a year; only seven frozen food items could be used. In addition, in efforts for best acceptability by the astronauts, many items were mixtures of foods and thus not conducive to exactness of composition in their production. Although these foods were far from ideal for balance studies, nevertheless, by skillful, lengthy consultations with the astronaut crewmembers, our dietitians developed for each crewman, sequences of six daily menus of similar elemental composition which were rotated on a regular schedule throughout the preflight, in-flight and postflight study phases. Whenever a particular food could not be consumed, a system of rapid calculation and provision of supplement tablets for pertinent elements helped to maintain dietary elemental constancy. During the flight phase, the crew's evening report included the relatively infrequent dietary omissions, rapid ground calculations were made for deficits in key elements and the correct number of supplement tablets or capsules prescribed up to the flight crew; these previously stowed supplies of tablets (or capsules) were taken the next morning.

Our relative success in dietary control is indicated in table I which shows for the Commander of the 59-day flight, as representative of the group, the phase-by-phase means of *actual consumption* of a few key elements and shows also the standard deviations from these means of day-by-day actual consumption. No significant differences occured from phase-to-phase.

TABLE I. MEAN (± STANDARD DEVIATION) DAILY DIETARY INTAKE, COMMANDER OF SKYLAB 3 (59-DAY FLIGHT)

	Preflight	In-flight	Postflight
Kcal	2732.0 (± 113)	2781.0 (± 259)	2940.0 (± 149)
Protein, g	95.0 (± 5)	85.0 (± 11)	96.0 (± 6)
Nitrogen, g	15.2 (± 0.9)	13.6 (± 1.17)	15.4 (± 1.0)
Potassium, mg	1517.0 (± 57)	1431.0 (± 116)	1537.0 (± 68)
Calcium, mg.	725.0 (± 31)	729.0 (± 72)	742.0 (± 40)

It should be emphasized that all food items were analyzed in representative samples for pertinent elements and vitamins. All diets were found to be adequate in terms of recommended vitamin intakes. However, because of concern for possible effect on the vitamins previously stowed in the Workshop from the high temperatures in the early days after launch, a supplemental vitamin capsule of RDA level was taken daily by each crewman on Skylab 3 and 4 (before, during and after flight).

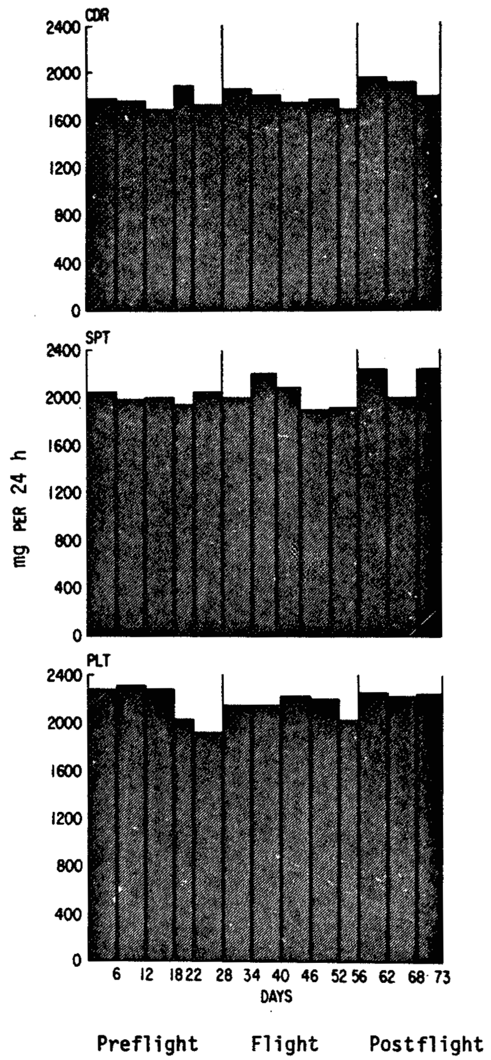
Twenty-four hour urine collections were made throughout the studies. In-flight, because of limitations in return weight and volume approximately 120 milliliter aliquots of each day's urine collection were taken, frozen and returned to Earth, using a very complex system because of the absence of gravity. In weightlessness there are difficult technical problems of collecting urine, separating liquid from air and taking a well-mixed measured aliquot, all without the aid of gravity which we so take for granted in our clinical research units and laboratories. In addition, because volume cannot be measured in the weightless state in the same way as on Earth, in-flight 24-hour urine volumes were determined by a tracer dilution technique, using lithium chloride pre-injected into the 24-hour collection bags. In-flight stool samples were dried in the Workshop and returned to Earth *in toto*.

RESULTS

Urinary creatinine excretion, (shown in figure 2 for the 28-day flight for three astronauts) revealed considerably more fluctuation than is found under ideal research unit urine collection conditions, but the values were consistent enough to indicate that average 24-hour urinary creatinine excretion was not changed by space flight.

Figure 3 shows the urinary calcium excretion for the 28-day flight. Urinary calcium in-flight increased steadily to a plateau in virtually the same pattern and degree as previously seen in bedrest studies. Also as seen in bedrest, interindividual variation occurred in degree of loss; the peak reached during the latter part of flight was from 80 percent greater to more than double the control, preflight levels. During recovery, postflight, urinary calcium excretion subsided promptly toward control levels.

Figure 4, for the 59-day flight, shows the same pattern of gradual rise in two crewmen and a rather abrupt rise in the third, and also shows interindividual variation in degree of loss, which in one was to much more than double control levels.



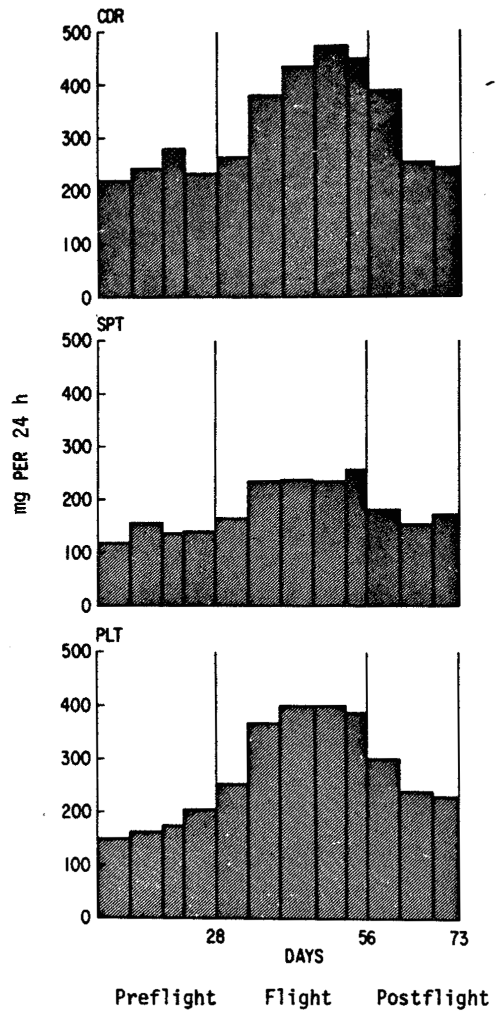


Figure 2. Urinary creatinine excretion, in means for 4- to 6-day metabolic periods, in the Commander (CDR), Scientist Pilot (SPT) and Pilot (PLT), of Skylab 2, before, during and after this 28-day flight (Skylab 2).

Figure 3. Effect of space flight on urinary calcium excretion in the astronauts of the 28-day flight (Skylab 2).

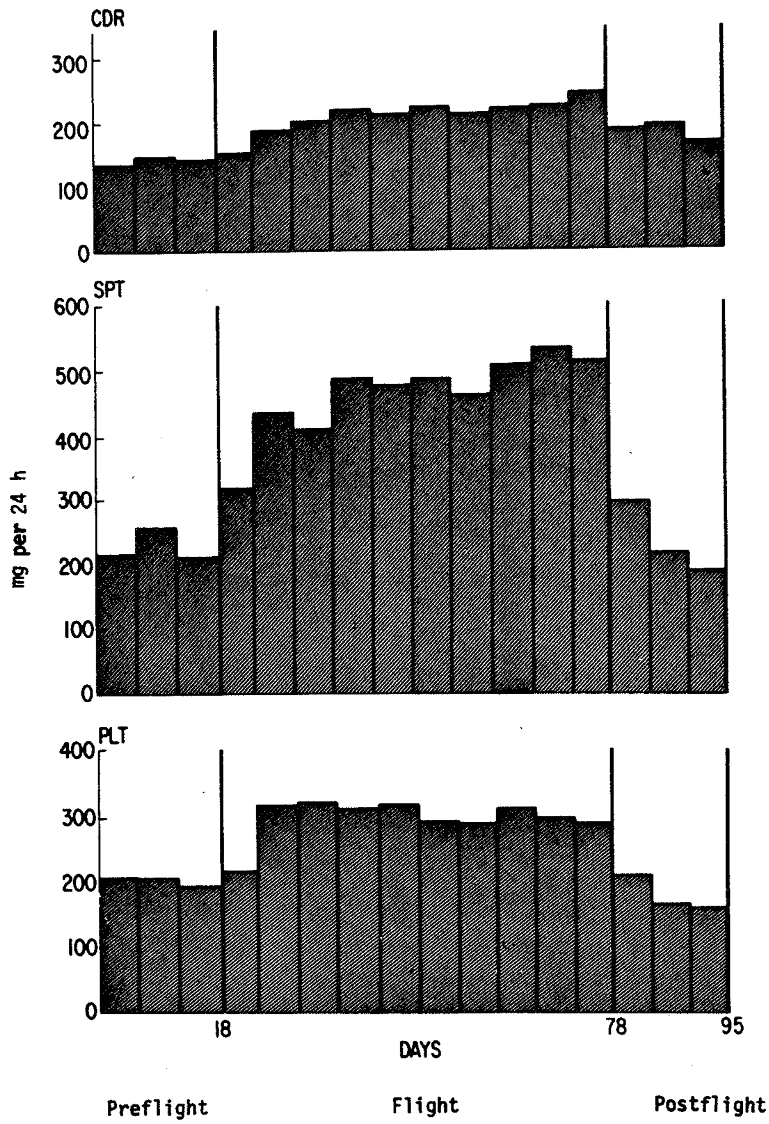


Figure 4. Effect of space flight on urinary calcium excretion in the astronauts of the 59-day flight (Skylab 3).

Urinary calcium data in the 84-day flight (fig. 5) showed the same characteristics, plus the added point of interest of no suggestion of decline toward the end of the flight in the high level of excretion.

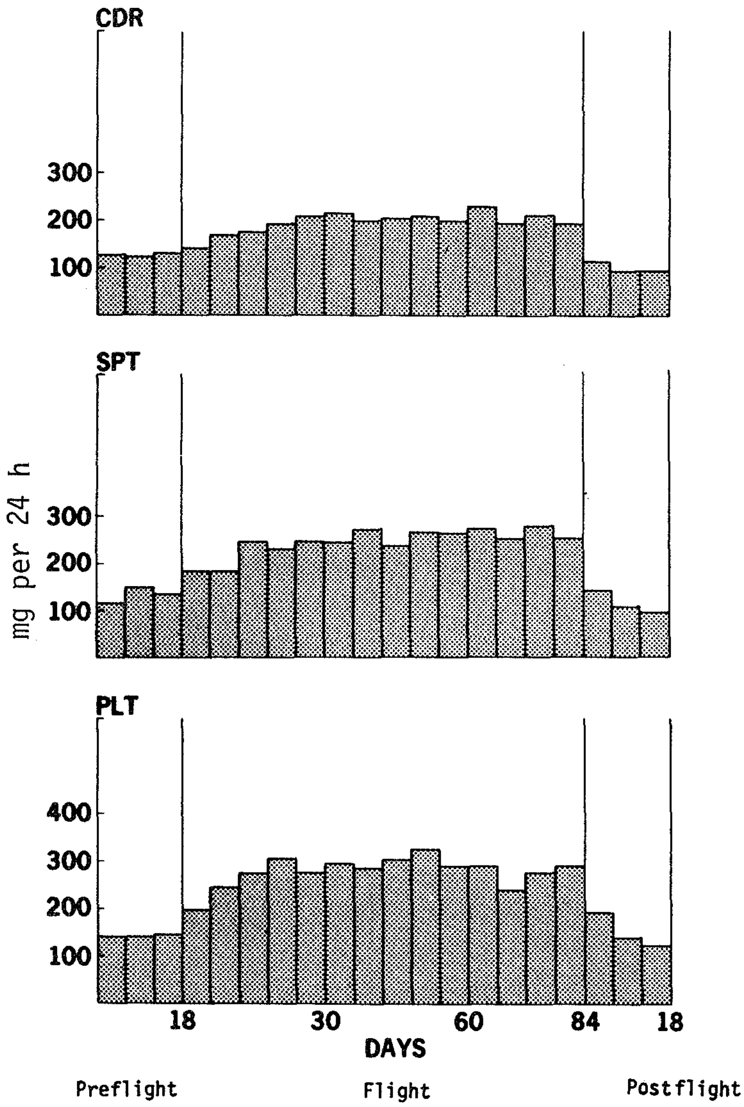


Figure 5. Effect of space flight on urinary calcium excretion in the astronauts of the 84-day flight (Skylab 4).

Urinary hydroxyproline (indicative of skeletal turnover and breakdown) increased in flight with considerable interindividual differences; the mean increase for the six crewmen of the first two flights was 33 percent.

Figure 6 displays the calcium balances for the 28-day flight; fecal calcium increased during flight in one crewman (Commander) and decreased slightly in the other two, and the balance became negative in two crewmen and changed imperceptively in the third (Scientist Pilot).

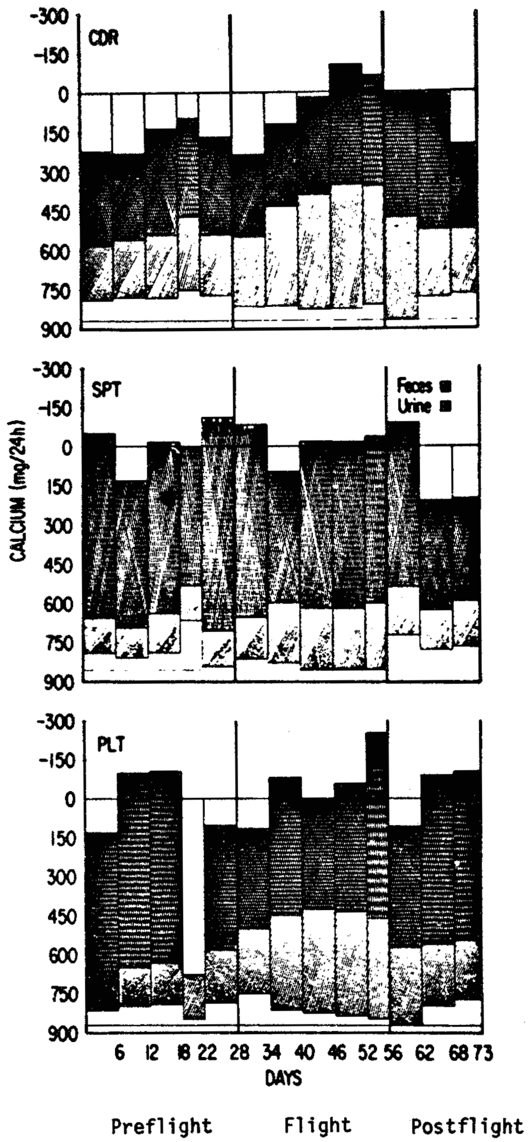


Figure 6. Calcium balances before, during and after space flight in the astronauts of the 28-day flight. In this and subsequent balance graphs the data are plotted in conventional Albright-Reifenstein style, the intake downward from the zero base-line, then urinary (light shading) and fecal (heavy shading) excretion upward from the intake lines; shaded areas above the zero baseline indicate negative balance or loss.

For the 59-day flight, the negative shift in calcium balance was more apparent (fig. 7), resulting from increases in both urinary and fecal calcium. The mean *shift* in calcium balance for all six crewmen from control phase to the last 16 to 18 days in-flight was minus 184 mg/day. The mean negative calcium balance during the second month in space for the three astronauts on the 59-day flight was 140 mg/day. This calcium loss was of the same order of magnitude as occurred in the early bedrest-immobilization study (1). Analyses of fecal calcium for the 84-day flight are still undergoing checking and reanalysis.

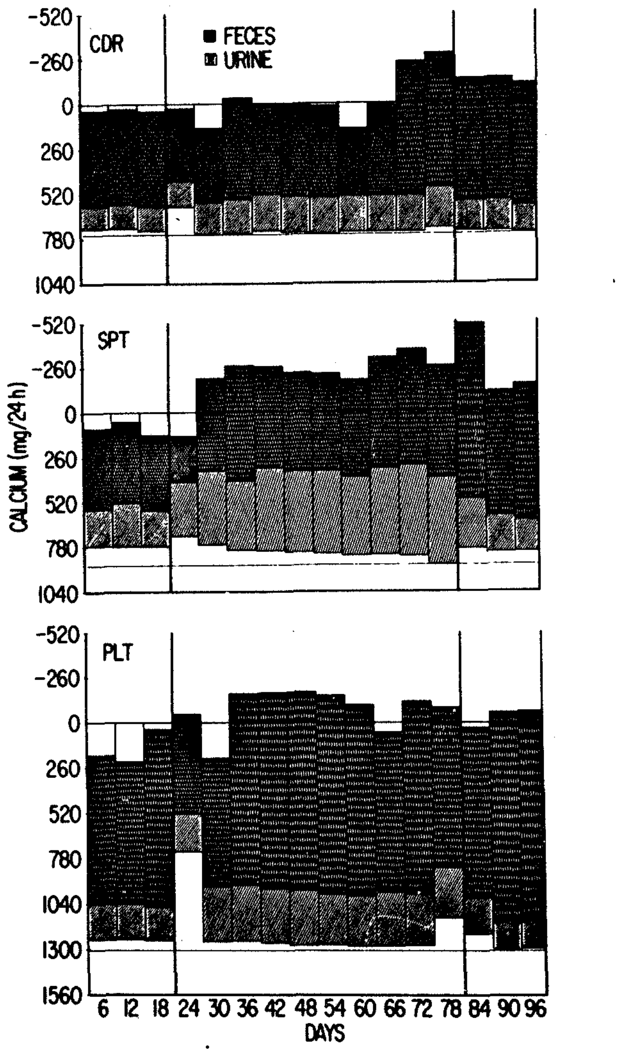


Figure 7. Calcium balances before, during and after space flight in the astronauts of the 59-day flight.

Phosphorus balance data (fig. 8) show for Skylab 2 a distinct increase in-flight in urinary phosphate, a small increase in fecal phosphate, and negative balance in all. In the Skylab 3, the increases in urinary phosphate were less marked than in Skylab 2, for reasons that are not apparent at this time. The mean negative shift in balance in Skylab 3 was 222 mg/day, in comparison with very nearly 400 mg/day in Skylab 2. In Skylab 4 the increases in urinary phosphate were again to about the same extent as in Skylab 2.

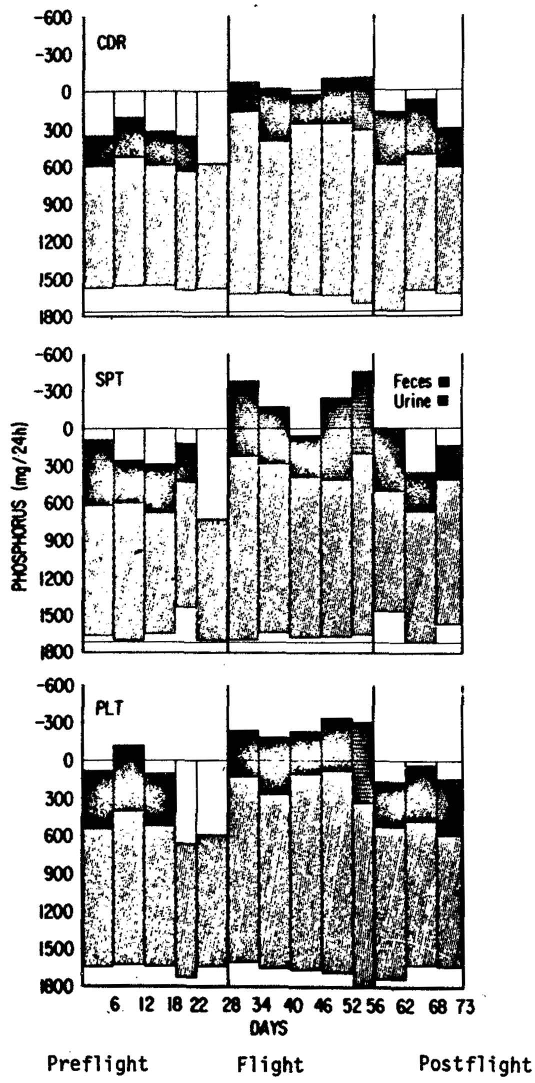


Figure 8. Phosphorus balances before, during and after space flight in the astronauts of the 28-day flight.

Nitrogen balance data (fig. 9) in-flight on Skylab 2 revealed a pronounced increase in urinary nitrogen excretion, while fecal nitrogen remained characteristically unchanged. In the 59-day flight (fig. 10), the highly negative balance of the first 6-day period was due to the lowered intake resulting from marked anorexia during the first two to three days in the new weightless environment; nitrogen balance continued negative for a few weeks and then was only slightly positive despite high protein and calorie intake levels. The mean shift in nitrogen balance (for the 6 crewmen of the first two flights) from preflight phase to flight was 4.0 g/day. In the 84-day flight increases in urinary nitrogen excretion of similar magnitude were observed (fig. 11).

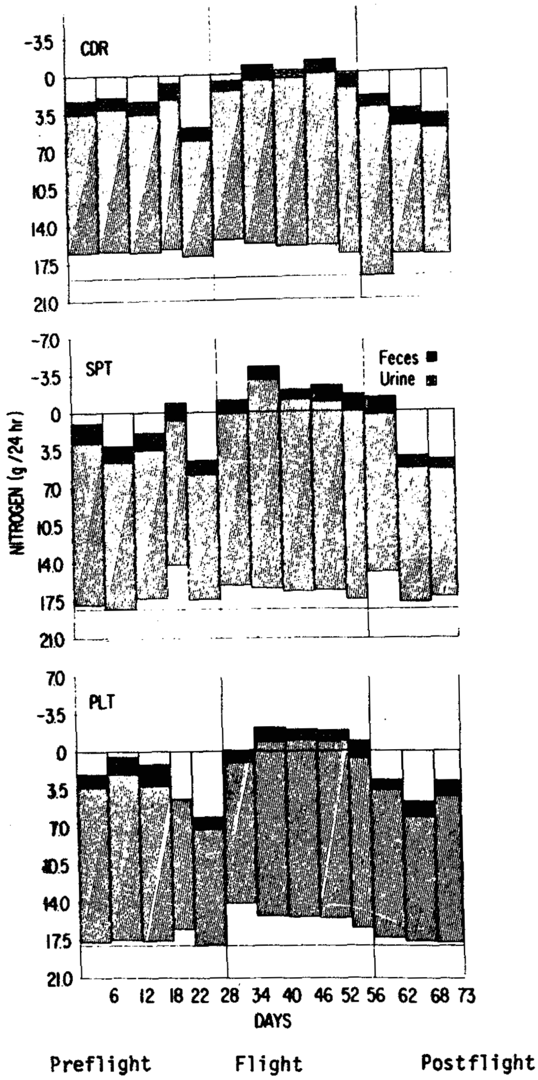
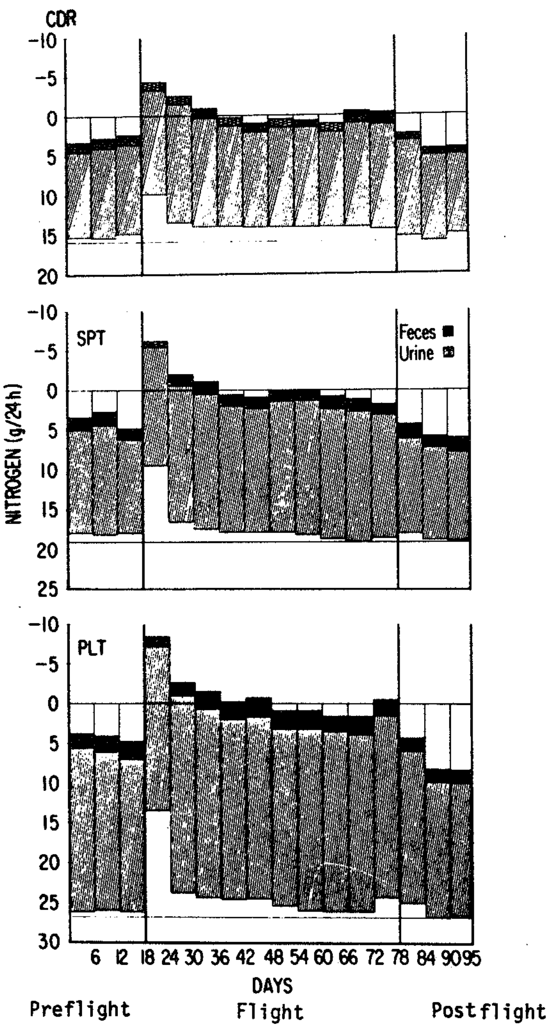


Figure 9. Nitrogen balances before, during and after space flight in the astronauts of the 28-day flight.



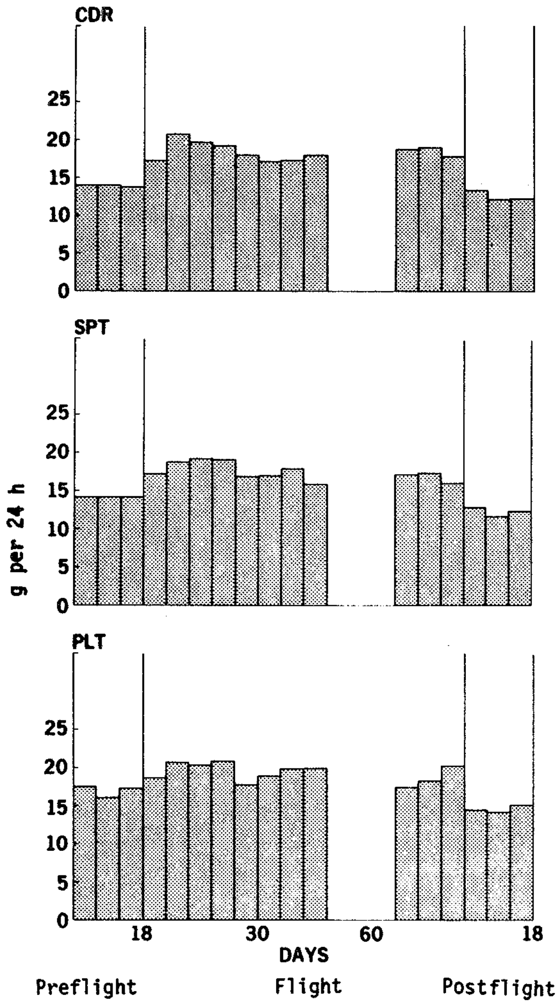


Figure 10. Nitrogen balances before, during and after space flight in the astronauts of the 59-day flight.

Figure 11. Urinary nitrogen excretion before, during and after space flight in the astronauts of the 84-day flight. The 18-day mid-flight gap in the graph is due to the fact that analyses had not been completed at the time of preparation of the graph.

Magnesium excretion in the urine increased during the in-flight phases of all three Skylab flights, with considerable interindividual variation and, for reasons that are not clear, to a somewhat lesser extent in the 59-day Skylab 3 than in the other two flights. Figure 12 presents the magnesium balances for Skylab 2, showing modest increases in urinary magnesium and the balances less positive but not true loss of the element.

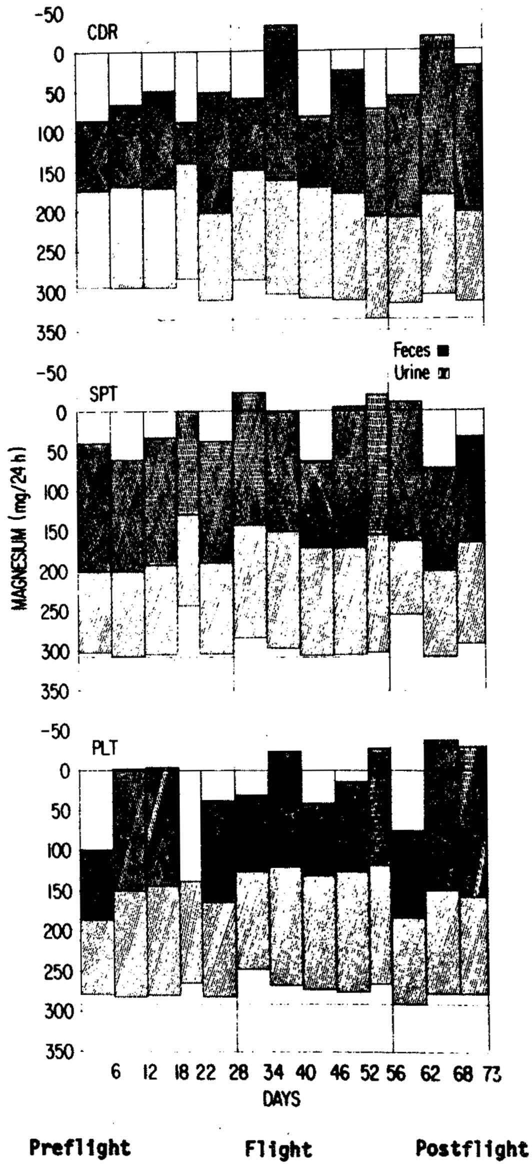


Figure 12. Magnesium balances before, during and after space flight in the astronauts of the 28-day flight.

Potassium balances became slightly less positive during flight, in line with other measurements suggesting potassium loss from the body, and indicated significant retention of this element in the recovery phase. Figure 13 shows the potassium balance data for Skylab 2. The changes were similar in Skylab 3.

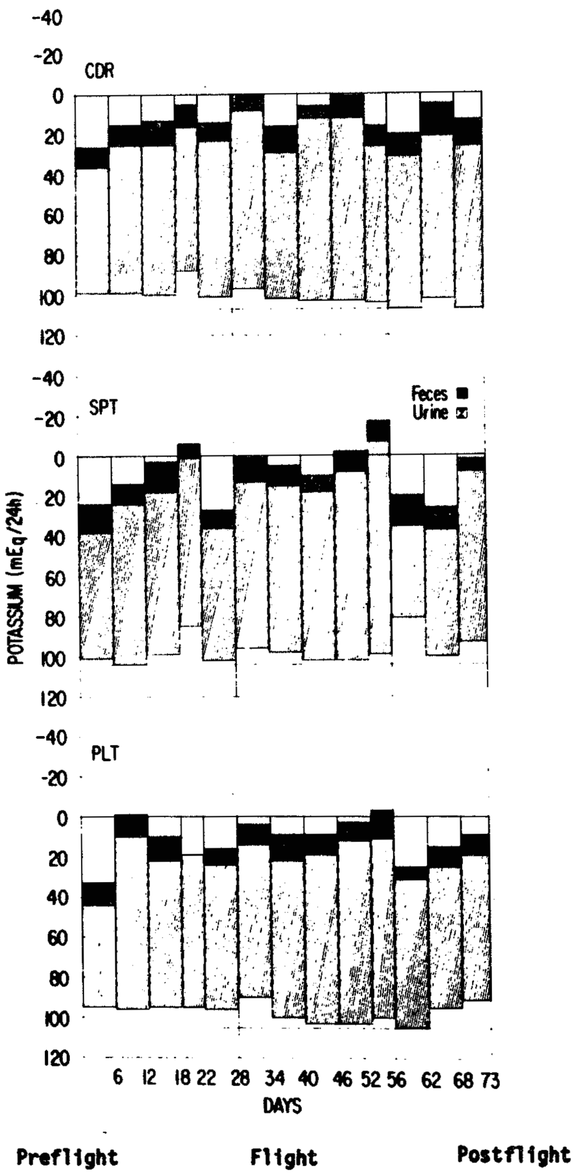


Figure 13. Potassium balances before, during and after space flight in the astronauts of the 28-day flight.

The sodium balance data for Skylab 2 and 3 also indicated modest negative shifts during flight. Sharp sodium retention occurred in all crewmen during the first few recovery days after each of the flights. Figure 14 shows the data for Skylab 2.

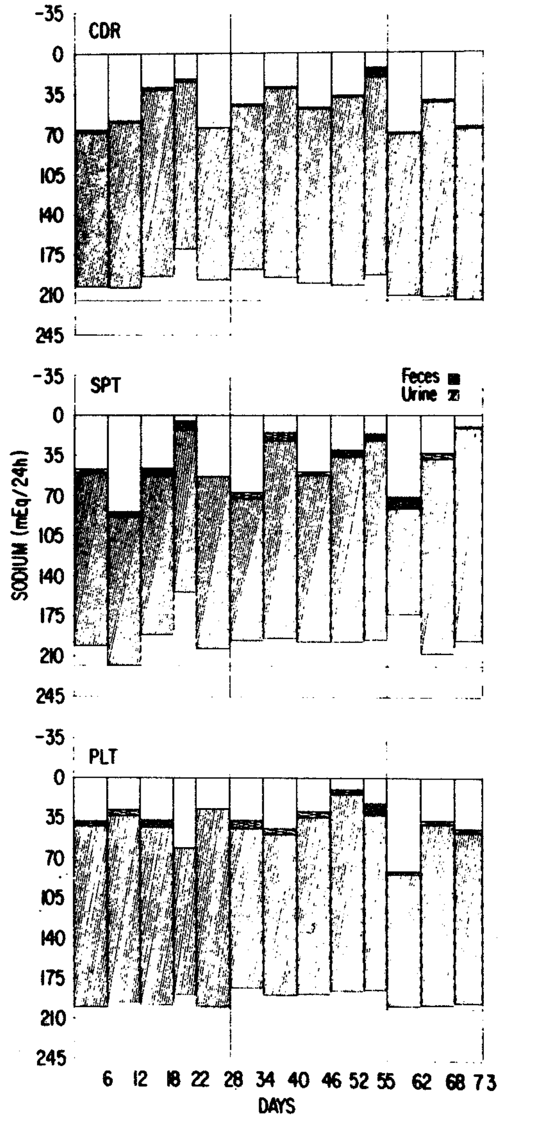


Figure 14. **Sodium balances before, during and after space flight in the astronauts of the 28-day flight.**

The potassium and sodium balance data and the significance of the changes therein will be discussed in the presentation of the M073 Endocrine Hormone and Body Fluid Study.

COMMENT

The urinary creatinine data obtained in both the 28 and 59 day Skylab flights settled a matter in doubt since Gemini VII in 1965. The Skylab data showed that, despite greater fluctuation than is seen under ideal research ward conditions, the average 24-hour urinary creatinine excretion was not changed by space flight. Thus the assumption made to this effect in order to salvage the Gemini VII urinary metabolic data was valid.

The increases in urinary calcium were strikingly similar in both pattern and degree to the rises in urinary calcium seen in bedrest. In addition, as compared with immobile bedrest (1), the negative shift in calcium balances during flight in the six Skylab 2 and Skylab 3 crewmen was of the same magnitude, and the mean actual calcium loss of the three 59-day flight crewmen was virtually identical. Although the total calcium loss rate generated by the second month in space (approximately 4 grams per month or 0.3 to 0.4 percent of total body calcium per month), appears small in relation to the whole skeleton, the similarity to bedrest in pattern and degree, as well as failure to show any tendency to abatement in three months' time, makes it necessary to deal with an assumption that mineral loss might continue for a very long indefinite time. Since mineral is lost differentially in greater total amounts from trabecular areas of bone, one must consider the possibility that in very long space flights local area losses of mineral of a degree equivalent to osteoporosis visible by ordinary X-ray would take place and that the strength of critical bones would be endangered. In paralytic poliomyelitis (5) long bone rarefaction visible by X-ray appeared at a mean loss of 2.0 percent of total body calcium; in these paralyzed patients in whom the calcium loss rate was about double that in immobile bedrest and in the 59-day space flight, osteoporosis was first seen within two to four months. Assuming that it would continue, the calcium loss rate of 0.3 to 0.4 percent per month observed in Skylab takes on clearer and more ominous significance when it is realized that flights to Mars and return, when ultimately conducted, will take from one and one-half to three years.

The increased excretion of nitrogen and phosphorus, also similar to that in bedrest, reflected substantial loss of muscle tissue, which was clearly observed in the astronauts' legs. Both muscle and mineral loss occurred despite an exercise regimen on all flights, which was extremely vigorous on the second and third flights.

We must conclude that although it seems reasonable to predict musculoskeletal "safety" in space flight for up to probably six to nine months, capable musculoskeletal function is likely to be impaired in crews on space flights of extreme duration *unless protective measures can be developed*. The likelihood of need for protective measures in flight is accentuated by the following consideration: although the bone losses thus far observed have been reversible upon return to normal gravity (or to ambulation after bedrest), no observations are available to permit estimation of a magnitude of loss that would represent a "point of no return". Thin trabeculae in bone can be returned to normal thickness but, from our present understanding of the adult skeleton, completely lost trabeculae cannot be restored.

Despite the threatening import of these Skylab mineral balance studies, they should not be interpreted as indicating a bar to long space flights. They do, however, clearly suggest that more work must be done, primarily in ground-based research, to provide techniques or procedures which, used in flight, will give reasonable assurance of healthfully functioning astronaut skeletal systems during and at the end of extremely long flights.

Finally, these observations may have significance for Earth medicine. In reminding us of the deleterious effects of disuse on bone mass, they reemphasize the importance of direct physical longitudinal stress (weight bearing) to the integrity of bone. In research on osteoporosis, greater attention than heretofore might be given to this factor for the possible value of *increased* weight-bearing stress as a deterrent *to* or even as aid to correction *of* this extremely prevalent bone disorder.

SUMMARY

A metabolic study of the effects of space flight on various chemical elements, particularly those with special relevance to the musculoskeletal system, was carried out on the nine astronauts who participated in the three Skylab flights of 28, 59 and 84 days in 1973-74. The study required of the cooperating crewmen constant dietary intake, continuous 24-hour urine collections and total fecal collections for 21 to 31 days before each flight, throughout each flight and for 17 to 18 days postflight.

Increases in urinary calcium during space flight and in-flight changes in calcium balance were closely similar in degree to those found in immobilization-bedrest. Similarity to bedrest in pattern of urinary calcium increases and of total calcium shifts suggested that calcium losses would continue for a very long time. Significant losses of

nitrogen and phosphorus occurred, associated with observed reduction in muscle tissue. Both mineral and muscle losses occurred despite vigorous exercise regimens in flight. It was concluded that unless protective measures can be developed, capable musculoskeletal function is likely to be impaired in space flights, ultimately to be conducted to Mars, of one and one-half to three years duration.

ACKNOWLEDGMENT

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PHYSIOLOGICAL MASS MEASUREMENTS IN SKYLAB

William E. Thornton, M.D., and Col. J. Ord, M.D., U.S.A.F. M.C.*†

ABSTRACT

One of the first changes noted in man following space flight was a loss in weight. To study the mechanism of such changes during flight, intake/output balance studies and measurements of crew mass were required. These measurements depended on the availability of nongravimetric mass-measurement devices. Such devices were flown and successful operation was demonstrated for the first time during Skylab missions. Electronically timed spring/mass oscillators were used to routinely determine all crew food residue and fecal masses to accuracies of a few grams. Daily body mass measurements were made with errors of a small fraction of a pound.

Two general patterns of body mass loss, usually mixed, were apparent. The first is a more or less continuous loss beginning before flight with an increase in rate of loss during flight. A second pattern is indicated by relative stability except for a small loss during the first few days of weightlessness with a reciprocal gain during the first few days after flight. Interpretation was complicated by heat stresses, changing exercise, and increased food as the missions progressed. However, the following observations are consistent with the data: a surprisingly high metabolic cost occurred on the mission; a metabolic loss was present in all crewmen except the Skylab 4 Commander; and a small fluid loss, on the order of a liter, appears to occur during the initial few days of weightlessness followed by a reciprocal change on return to normal gravity. This latter loss is small and self-limited, and appears to be the only obligatory loss with other losses seen to date being primarily metabolic.

INTRODUCTION

I would like to thank you for this opportunity of telling you about our medical experiments on Skylab, some of the things we discovered, and a few we did not. Many of you in the audience have worked directly or indirectly on these experiments and made these results possible.

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*Astronaut Scientist, National Aeronautics and Space Administration - Lyndon B. Johnson Space Center, Houston, Texas

†Hospital Commander, Scott Air Force Base

Some of us and some of you, have waited quite a while for these results; in the case of this experiment almost eight years. Nine years ago while working on the Manned Orbiting Laboratory Project at the Aerospace Medical Division of the Air Force, we concluded that one of the first priorities in space medical research was to determine the cause and time course of the weight loss which always seemed to accompany space flight. It was obvious to us and to many others that a carefully controlled intake/output study with accurate daily mass measurements in-flight would be required. At that time, the insurmountable problem to such a study was the lack of an instrument for nongravimetric mass measurement. The first priority, then, was development of a mass measurement device which did *not* depend on weight. Development was started and by 1966 I had built protypes of the instruments flown on Skylab.

As time went on, the Manned Orbiting Laboratory program had an unfortunate end, we had mass measuring devices, and Nasa had a planned in-flight balance study without a mass measuring device so we formed a joint effort which was implemented on Skylab. This morning, I will describe the methods used to measure mass in weightlessness since this technique had not been used before, and then, as time allows, I will discuss the results obtained, results which affect many other experiments and future planning.

Gravimetric mass determination or weighting is such a simple and accurate process that no other methods have been developed or really needed since the Egyptians began using balances 5000 or more years ago. The only practical alternative to gravimetric attraction is some determination of the mass' inertial property. The method chosen to do this in 1965, and not necessarily the present method of choice, was the spring-mass oscillator constrained to linear motion.

PROCEDURE

Figure 1 is a schematic of the method. A sample mass is placed between two springs and constrained to linear motion in the longitudianl axes of the springs. If the mass is displaced from its rest postion X_0 to a new position X and released, it will undergo essentially undamped natural ocillation at a frequency given by the well known relationship shown. If this period of oscillation is accurately measured by a high resolution timer, mass may be calculated. Rather than attempt a calculation based on machine quantities such as spring rates, a calibration which would have inevitable errors from gravitational effects, an in-flight calibration using precision masses was done.

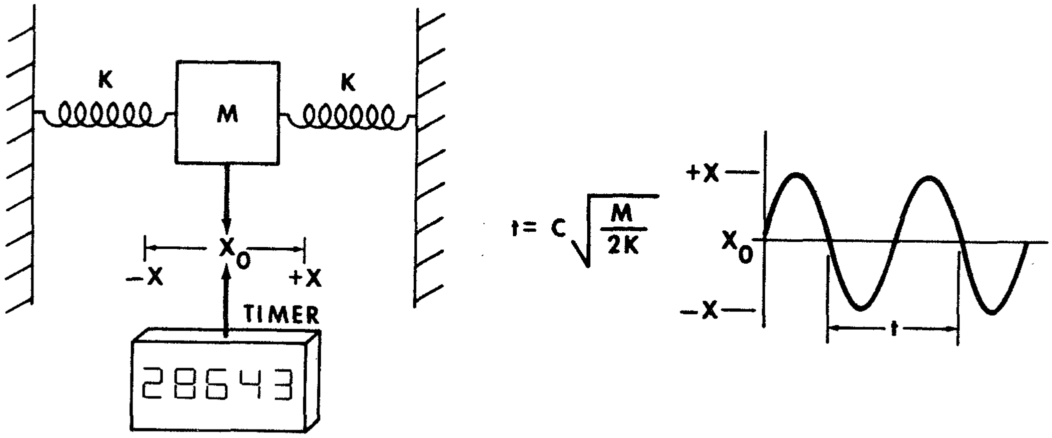

Figure 1. Schematic of Spring/Mass Oscillator and its motion.

Figure 2 is a plot showing a calibration record chosen at random from one of the small or specimen mass measuring devices used on Skylab and it simply shows that it follows the theoretical curve reasonably well. It really was chosen at random for linearity is usually approximately 0.1 percent and normally no points can be found off the curve. With care and by using a modified calibration curve, accuracy of 0.01 percent, or better, can be obtained with solid masses.

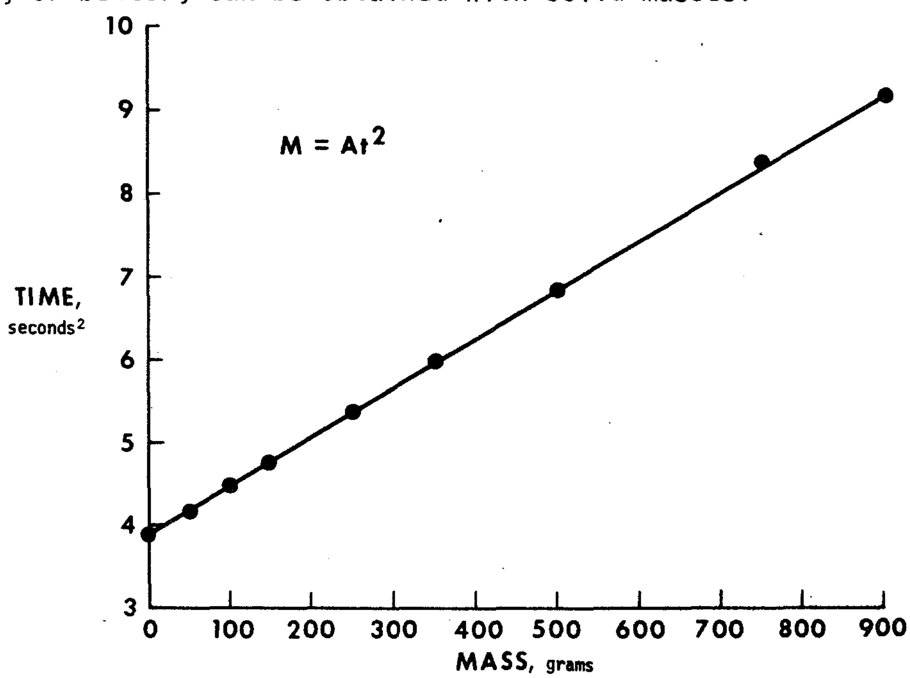

Figure 2. Calibration curve Skylab 2 small mass measuring device, mission day-9.

This system is sensitive to any nonrigidity (slosh) in either sample or mounting and to any external or sample oscillation (jitter) if either of these effects are near the fundamental frequency of oscillation. Thus, in the case of some food, liquids, and the human body, special arrangements must be made.

Let me describe these arrangements and the in-flight operation by showing you a film of the hardware that was flown on Skylab.

This film (16 mm ciné film shown) was made in the Skylab crew trainer which is as close as possible to the in-flight arrangement. Two small instruments each with a capacity of one kilogram were flown - one in the Wardroom which I'm now entering. All food was carefully weighed, analyzed, and identified preflight. Any package which was not totally consumed, and only six or so out of the thousands were not, was placed in the device shown here, and measured.

This is the oscillating specimen tray, and the perforated elastic sheet holds the food package to it. Operation consists of turning the counter on, adjusting it to, and rotating and holding the lever which successively unlocks, displaces, and then releases the specimen tray.

The time for three periods of oscillation is then registered by the opto-electronic counter to 10 seconds. This time is recorded and voice relayed to Earth where mass is calculated and suitable nutritional adjustments are made to meals for the next day.

Now moving on to the Head, there is a second and identical instrument on which all vomitus, of which there was only three or four samples, and all feces, collected in such bags, were measured. An onboard graphic conversion to mass was made to allow proper setting of the fecal drying timers. All fecal samples were dried and returned to Earth *in toto* with the oscillation time periods for anaylses.

Figure 3 shows a large or body mass measuring device with a capacity of 100 kilograms. A basal body mass was made by each crewman every morning after arising and voiding. The same type of clothing of known mass was worn each day and any extra objects were removed from the pockets. Although the human body is supposed to move as a single rigid structure below one cycle per second, this proved to be only approximately true; and it was necessary to reduce slosh to a minimum by folding the body into the most rigid configuration possible, as you see here, and to reduce the period of one cycle of oscillation to two seconds. Straps are necessary under weightlessness to constrain the body to the seat.

The same timer and timing arrangement is used as those on the Small Mass Measurement Devices. After strapping in, the seat is unlocked and cocked by the large handle. The timer is turned on and the device is adjusted to zero. One takes a breath, holds it to avoid "jitter" and then releases the seat to oscillate by means of a trigger on the hand bar. After three cycles of timing has has been completed, the period is recorded and returned to Earth where mass is calculated.

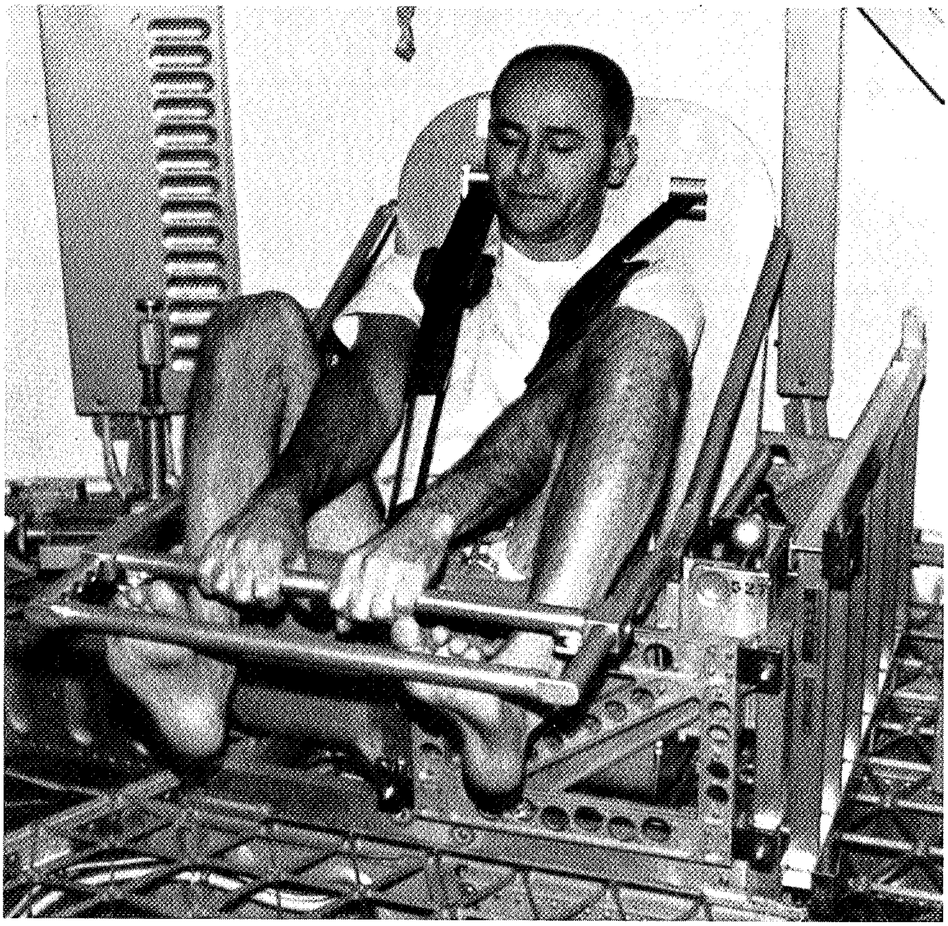

Figure 3. In-flight photo of Skylab 3 Commander making daily body mass measurement. "Chair" oscillates along back-to-front axis of subject. Timer is at the subject's left and the forward elastic flexure pivots may be seen (diagonal braced lightened frame).

Figure 4 is a record of the total *uncorrected* deviations of the Specimen Mass Measuring Device in the Head at the 50-gram calibration point. These points were taken over three missions as shown. Without going further into the engineering aspects, maximum error for food and vomitus samples, was less than three grams. Repeatability of body mass measurements was ±0.1 pounds, and absolute accuracy was between +1/4 and +1.0 pounds and probably nearer +1/4 pounds.

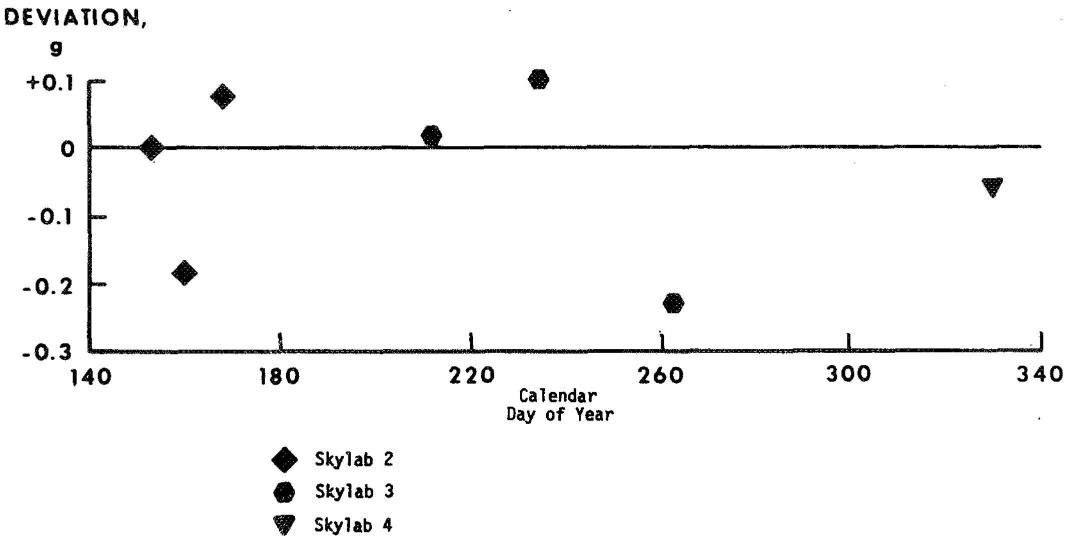

Figure 4. Variation in 50-gram calibration point, Small Mass Measurement Device - Skylab Mission

A number of hardware support measurements were made during the mission with excellent results: for example the 24-hour urine pools were measured to an accuracy of a few milliliters.

RATIONALE

Until Skylab, there was an unexplained loss of weight on every American and, so far as I know, Russian flight and in every astronaut except Alan Shepard* on Apollo 14.

There were three common theories to account for these losses:

- Under weightlessness, fluid was shifted from the lower portions of the body to the chest area where it was sensed as an excess and secreted by the kidneys in accord with the Gauer-Henry theory.

*Recent publication of data indicates a loss in this crewman also.

- At least a portion of the loss was sometimes thought to be metabolic since food quantities and opportunities to eat were frequently minimal.

- Under certain conditions there were periods of high physical activity with heat and other stresses which resulted in rapid loss..

A comment may be in order: One often thinks of daily weights as a highly variable measurement, as indeed they are unless carefully made. But if they are carefully made under basal conditions and if the subject is on a controlled diet, losses of a fraction of a pound per week become not only detectable but significant. While a few ounces loss or gain per week is normally of no importance, if they are continued for months, especially under conditions which can't be altered, they become significant indeed.

The slides (figs. 5 to 13) I will show now are the plots of Skylab crew body weights - preflight and postflight from experiment M071 and the inflight equivalent weights measured with the Body Mass Measurement Device. The data has been smoothed by taking a three-day sliding average. These plots cover the period that the crew were on the Skylab diet.

The plots shown in figures 5 and 6 are from the Commander and Pilot of Skylab 2. The Scientist Pilot (fig. 7) had a similar curve with a total loss between the previous two shown. The first few days' data was lost during vehicle repairs, and this was also a period of heat stress. One sees a loss which began with initiation of the diet and accelerated during the mission itself. The sharp dip inflight was coincident with extravehicular activity. Immediately postflight, there was a transient increase in weight followed by a plateau. The predominant loss pattern of the first manned Skylab flight is consistent with a simple metabolic deficit.

While the losses were easily sustained in this short mission they could not be tolerated on missions of long duration. Even the 3-1/2 pound loss of the Commander is significant in a small crewman who launched with a body fat of less than 10 percent.

On Skylab 3 both food and exercise were increased, and we see a different pattern. The Commander was relatively stable preflight, had a sharp loss for the first few days in flight, and another loss near the end. On recovery, there was the usual increase and plateau

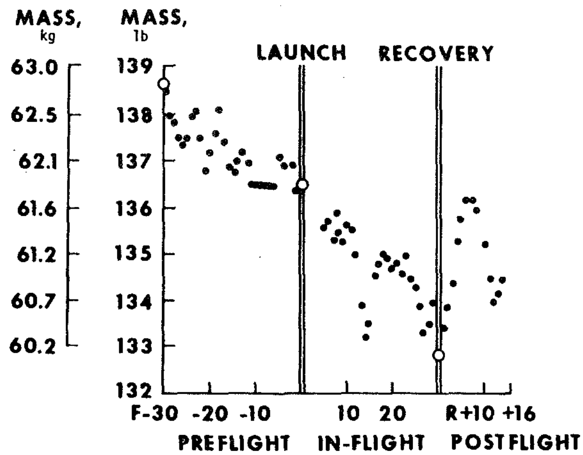

Figure 5. Body mass measurement of the Skylab 2 Commander.

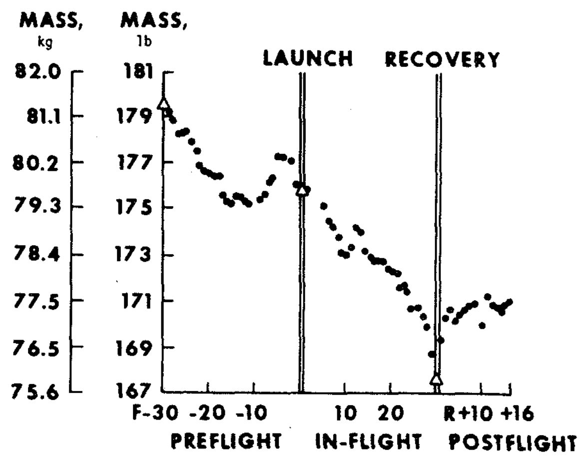

Figure 6. Body mass measurement of Skylab 2 Pilot.

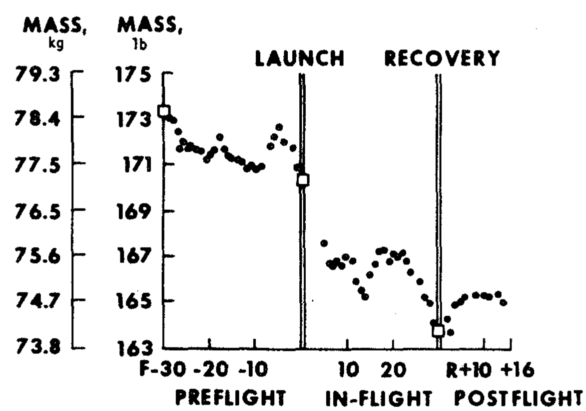

Figure 7. Body mass measurement of Skylab 2 Scientist Pilot.

or inflection point (fig. 8). The Pilot, had an almost identical curve (fig. 9). Remember, that these crewmen had nausea and were not eating properly the first few days, and that there was a period of increased activity, especially for the Pilot and Commander prior to entry. The Scientist Pilot had a sharp loss on exposure to weightlessness and a small continued loss in-flight consistent with a metabolic deficit and a typical recovery pattern (fig. 10). Here, I feel that we see two other loss mechanisms demonstrated.

From the time course of the losses and gains on orbital insertion and recovery, it seems reasonable to conclude that fluids are involved. This will be discussed further in a moment. At the same time, there are periods of increased stress, such as preparation for entry or extravehicular activity on Skylab 2 which temporarily exceed caloric intake.

On Skylab 4, food and exercise was again increased, and we have the second American astronaut in space who lost essentially no body mass in flight - the Commander (fig. 11). His profile shows a preflight gain, a small initial loss, and a postflight gain. His crewmen had losses similar to or smaller than the astronauts on Skylab 3 (figs. 12, 13).

At this point, we seem to have come full circle and have demonstrated that all three mechanisms originally proposed are operative. It would appear that the most significant on this mission was a simple metabolic loss. In further support of this, the average weight loss of all crewmen was plotted versus the normalized average caloric intake (fig. 14). The caloric data shown is the latest obtainable from the food section. Although the sample is small, the relationship seems clear, the three subjects off the "main line" relation were also the three crewmen with the smallest body fat -- all three well under 10 percent.

Caloric intake required for an extrapolated zero loss is extremely high indicating a surprisingly high in-flight metabolic cost.

It must be recognized that simply adding food to the diet is not the whole answer, for while this will assuage hunger and maintain mass, body muscle might be exchanged for fat. This closely related problem of exercise and conditioning will be discussed next.

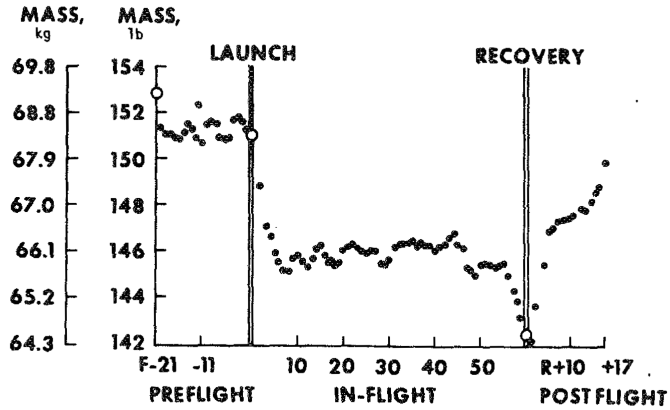

Figure 8. Body mass measurement of the Skylab 3 Commander.

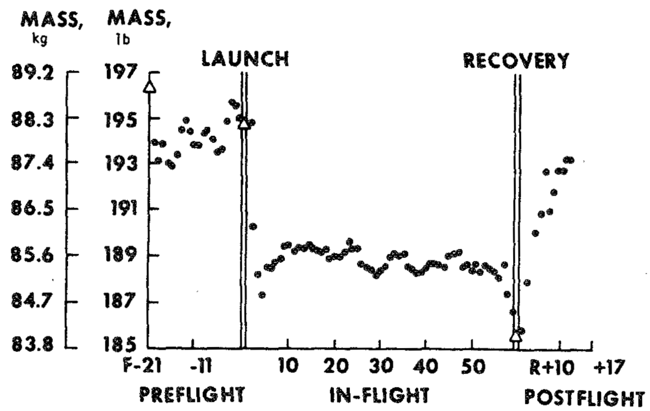

Figure 9. Body mass measurement of the Skylab 3 Pilot.

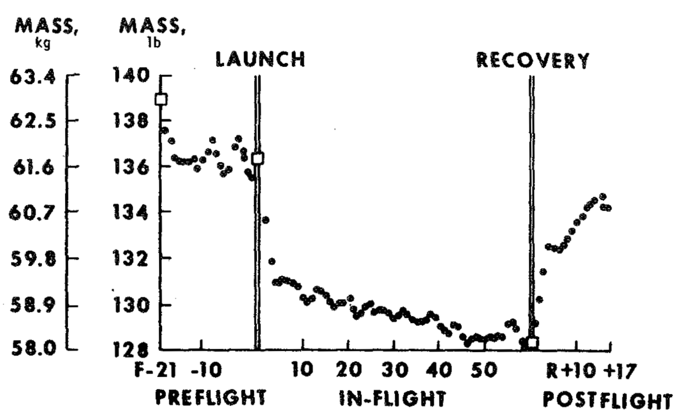

Figure 10. Body mass measurement of the Skylab 3 Scientist Pilot.

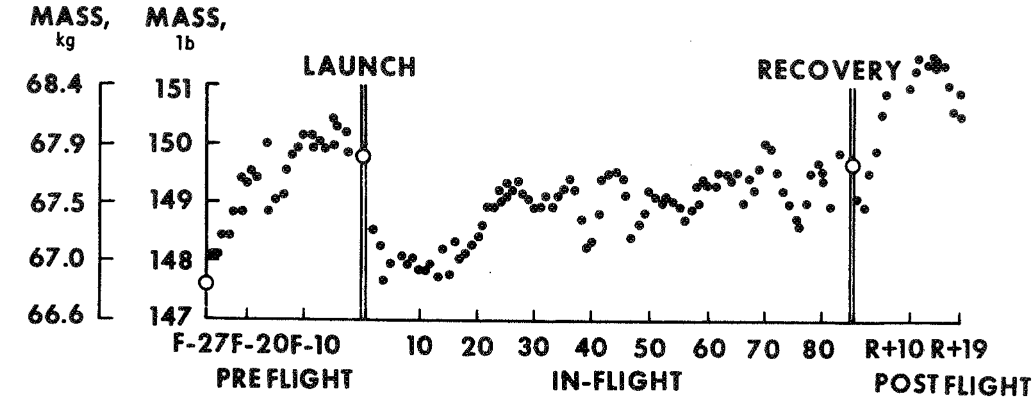

Figure 11. Body mass measurement of the Skylab 4 Commander.

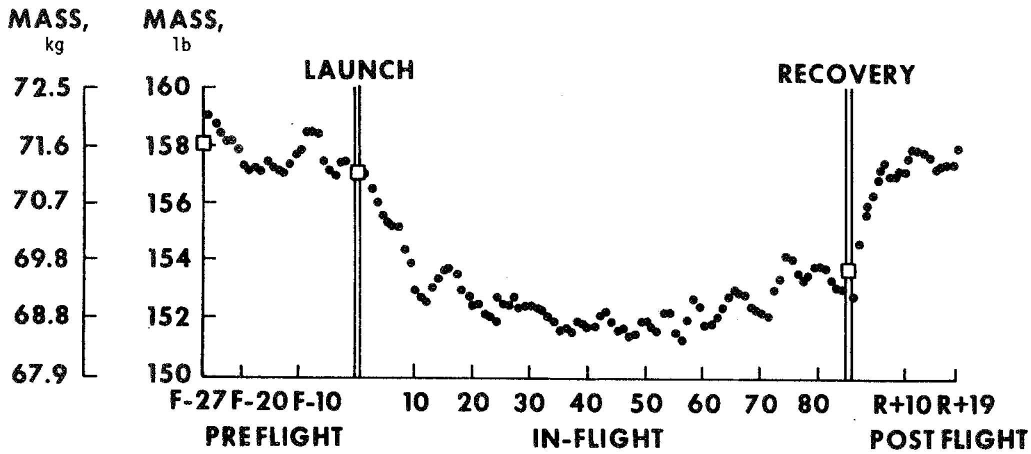

Figure 12. Body mass measurement of the Skylab 4 Scientist Pilot.

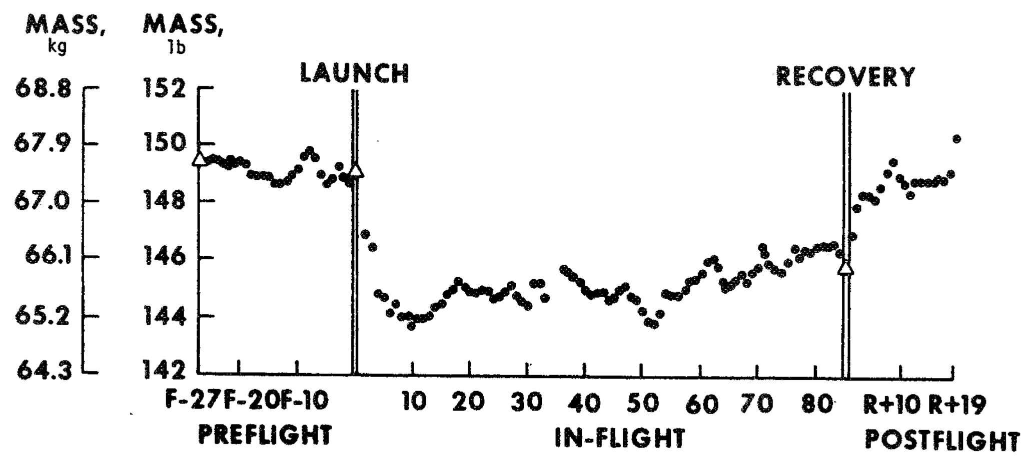

Figure 13. Body mass measurement of the Skylab 4 Pilot.

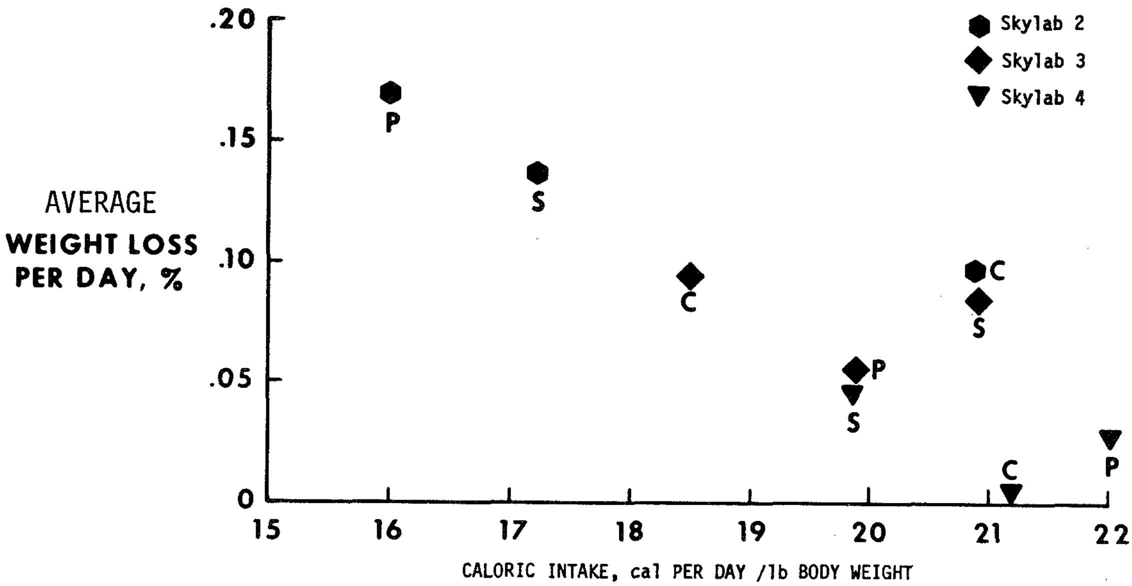

Figure 14. Weight loss *vs.* caloric intake for the nine Skylab astronauts in flight.

The plots in figures 15 and 16 are two-day sliding averages of crew mass from Skylab 3 and 4 for ten days following insertion and recovery to demonstrate fluid losses. On Skylab 3, there was a sharp loss of three to four percent of body weight over the first four or five days following exposure to weightlessness. On return to one-g, there was an approximate reciprocal gain. On Skylab 4, we see the same pattern in one crewman; the crewman who was nauseated and not eating and drinking, just as had been the case with all three Skylab 3 crewmen. The other two crewmen showed a much less pronounced drop, and on recovery, there was a smaller reciprocal gain except for the Scientist Pilot. It is my suspicion that transient fluid losses or gains will be small, probably on the order of one percent in crewmen who eat and drink adequate amounts throughout the mission. This intriguing question of fluid loss and the Gauer-Henry theory will undoubtedly be further addressed by the appropriate investigators to show routes and mechanism of loss and gain.

DISCUSSION

For the future; dietary standards must be revised to meet the metabolic requirements of given missions and tasks. In-flight studies of metabolic costs of realistic activities will allow better definition of overall requirements. The requirements on this mission with its

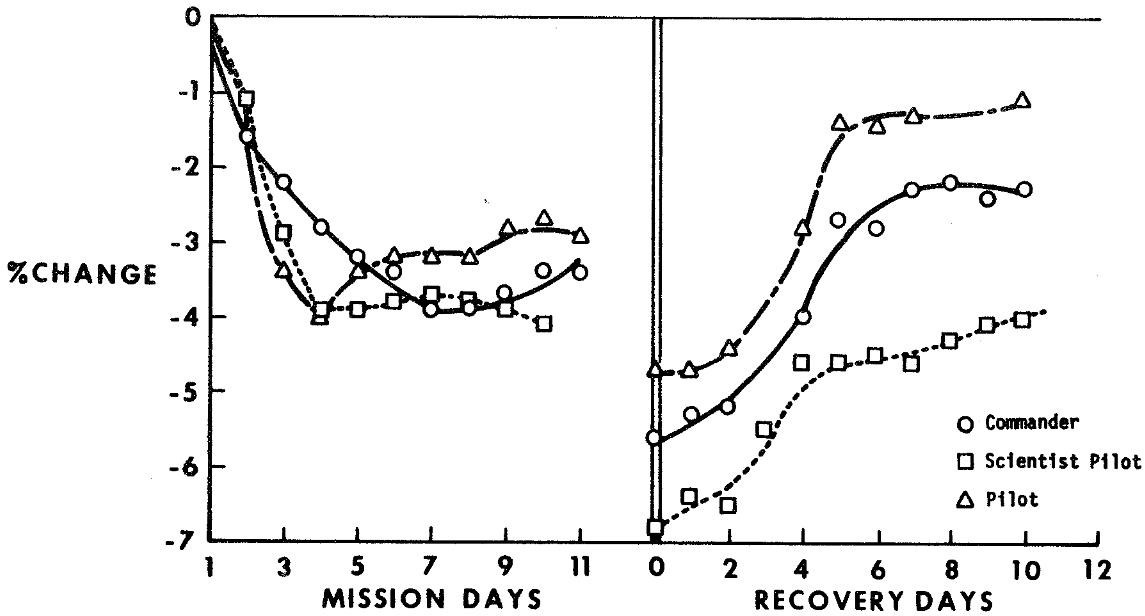

Figure 15. Body weight change Skylab 3 insertion and recovery.

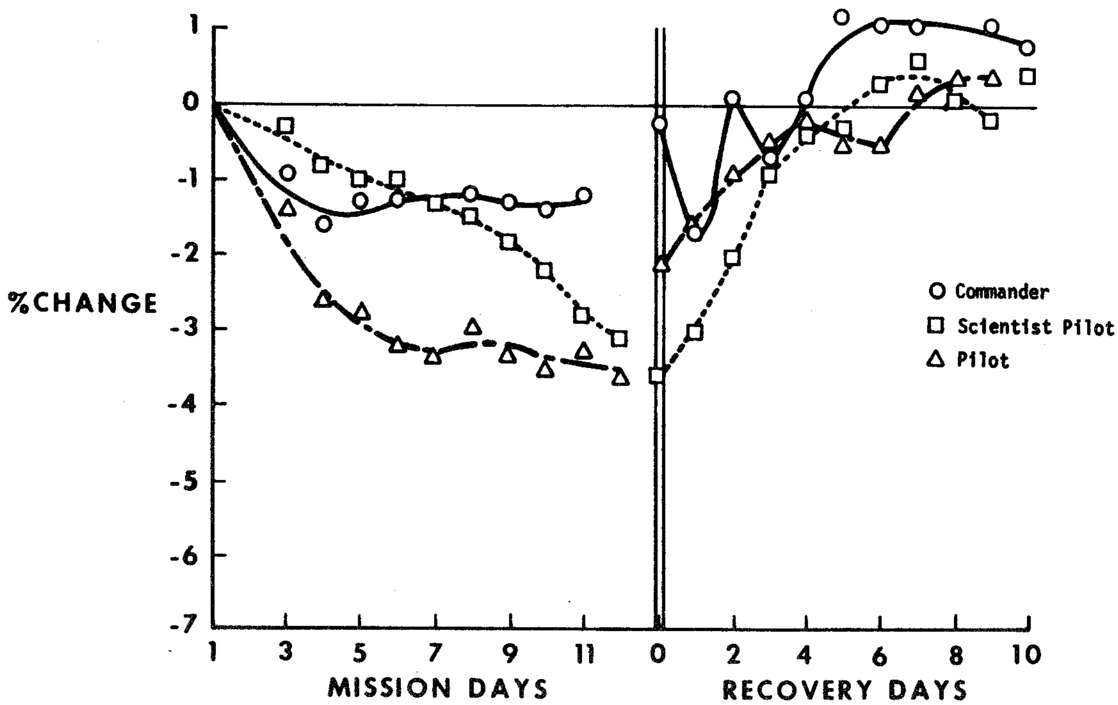

Figure 16. Body weight change Skylab 4 insertion and recovery.

jammed, 14-hour day work schedule should not necessarily be considered typical of all missions.

To those of you concerned with future planning; as long as man flies and measures in flight, he will continue to need mass measurements. Although the present system met the requirements, they were complex, heavy, and expensive. I trust that they will not become the accepted standard, for in the eight years since development of these devices, we have devised a number of other models with marked advantages over the spring/mass oscillator.

SUMMARY

In summary, we have demonstrated a new instrument for in-flight space operations and research, have demonstrated the previously unproven mechanisms of weight losses under weightlessness, and most importantly, helped to prove that the human body properly fed can sustain missions of long duration without significant obligatory mass loss.

ACKNOWLEDGEMENTS

Too many people have contributed to this project to list them all. A. G. Swan made the project possible by his unstinting financial and moral support especially in the early day of development. It would never have been demonstrated or flown without the superb model shop work and design contributions of the instrument shop at the U.S.A.F. School of Aerospace Medicine which included Messrs. Garbich, Rosenblum, Wright and above all McDougal. Dick Lorenz did an excellent electronic design for the prototype hardware as did William Oakey on the mechanical prototypes. Wray Fogwell suggested the flexure pivot as a simplification of the original design. Larry Dietlein, Weyland Hull, Paul LaChance and Sherm Vinograd at NASA were instrumental in establishing the mass measuring devices as experiments.

Flight hardware was constructed by Southwest Research Institute and the NASA project engineers were Vern Kerner and Ray McKinney.

BONE MINERAL MEASUREMENT - EXPERIMENT M078

John M. Vogel, M.D. and Sqn. Ldr. M.W. Whittle, M.Sc., M.B., B.S., R.A.F.*†

ABSTRACT

The probability of significant bone mineral loss being initiated by extended periods of weightlessness has been predicted on the basis of observations in bedrested and immobilized subjects. Radiographic estimates of bone mineral loss conducted on the crewmen of Gemini 4, 5 and 7 led to greater concern since the losses documented during these rather short missions were large. To test the validity of these observations, studies utilizing a newer and more precise technique were performed on six-to-nine month bedrested subjects. No mineral losses were observed in the radius and ulna and variable losses were observed in the *os calcis*. This variability was reconciled when the rate of loss was found to be correlated to the initial mineral content and inversely correlated with the baseline hydroxyproline excretion.

The mineral content of the distal right radius and ulna and the central left *os calcis* was measured preflight and postflight on the nine crewmen of the three Skylab manned missions using the photon absorptiometric technique. No significant mineral losses were observed in any of the three Skylab 2 crewmen. Only the Scientist Pilot of Skylab 3 and Scientist Pilot and Pilot of Skylab 4 had significant mineral losses in the *os calcis*. No losses in the radius and ulna were seen.

The losses observed generally followed the loss patterns observed in a heterogeneous group of bedrested subjects.

It is concluded that mineral losses do occur from the bones of the lower extremities during missions of up to 84 days and that in general, they follow the loss patterns of the bedrested situation. The levels of loss observed in the Skylab crews have been of no clinical concern but it was fortuitous that all of the Skylab 4 crewmen had high prediction terms.

INTRODUCTION

The probability of significant bone mineral loss being initiated by extended periods of weightlessness has been predicted on the basis of observations in bedrested and immobilized subjects. Radiographic

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estimates of bone mineral loss conducted on the crewmen of Gemini 4, 5 and 7 led to even greater concern since the *os calcis* losses ranged from 2 to 15 percent, the radius from 3 to 25 percent and the ulna from 3 to 16 percent (1). Subsequent reevaluation of this data led to the conclusion that there had been an approximate 6.7 percent overestimation of loss due to the inherent difficulties with the technique employed (2). Nevertheless, the magnitude of these mineral losses for 4 to 14 day missions if extrapolated to the longer Skylab missions could prove to be hazardous both in terms of potential fractures or in the production of renal stones.

Since the validity of the Gemini data needed to be reevaluated prior to the Skylab missions, fifteen bedrest volunteers were studied using a newer and more precise technique, namely, gamma ray absorptiometry.

METHOD

Bone mineral content was determined in the central left *os calcis* and the right distal radius and ulna using the photon absorptiometric technique. It employed an essentially monoenergetic photon source, the 27.5 KeV X-ray of Iodine-125, and a sodium iodide crystal scintillation detector. These essential elements are mounted on a scanner yoke in direct opposition to each other and collimated so that a 3 millimeter beam is similarly viewed by a 3 millimeter entrance collimator on the detector, (fig. 1). The yoke is mounted on a scanner which is able to scan a limb placed between the source and detector in a rectilinear raster pattern. When scanning the upper extremity the scanner is reconfigured as shown in figure 2. The limb to be scanned is placed in tissue equivalent material to compensate for the irregular thickness of tissue cover that surrounds the bone. The foot is placed in a Plexiglas® box filled with water (fig. 1), and the arm is encased in Superstuff® when placed on a platform between uprights (fig. 2).

The most distal two centimeter portion of the radius and ulna were measured and reported as mean mineral content in grams of ash per centimeter of bone length. The mineral content of the central two and one-half centimeter section of the *os calcis* is reported in mg/cm^2 of hydroxyapatite. Mineral content is obtained from the basic attenuation equation, (fig. 3). The count rate of the transmitted beam through the tissue and tissue equivalent is designated as $I_0{}^*$. Each data point through bone is designated as I. Transmission or absorbance through this segment is given as the log of the ratio $I_0{}^*/I$ and the sum of these values across the bone is proportional to the mineral content in this segment.

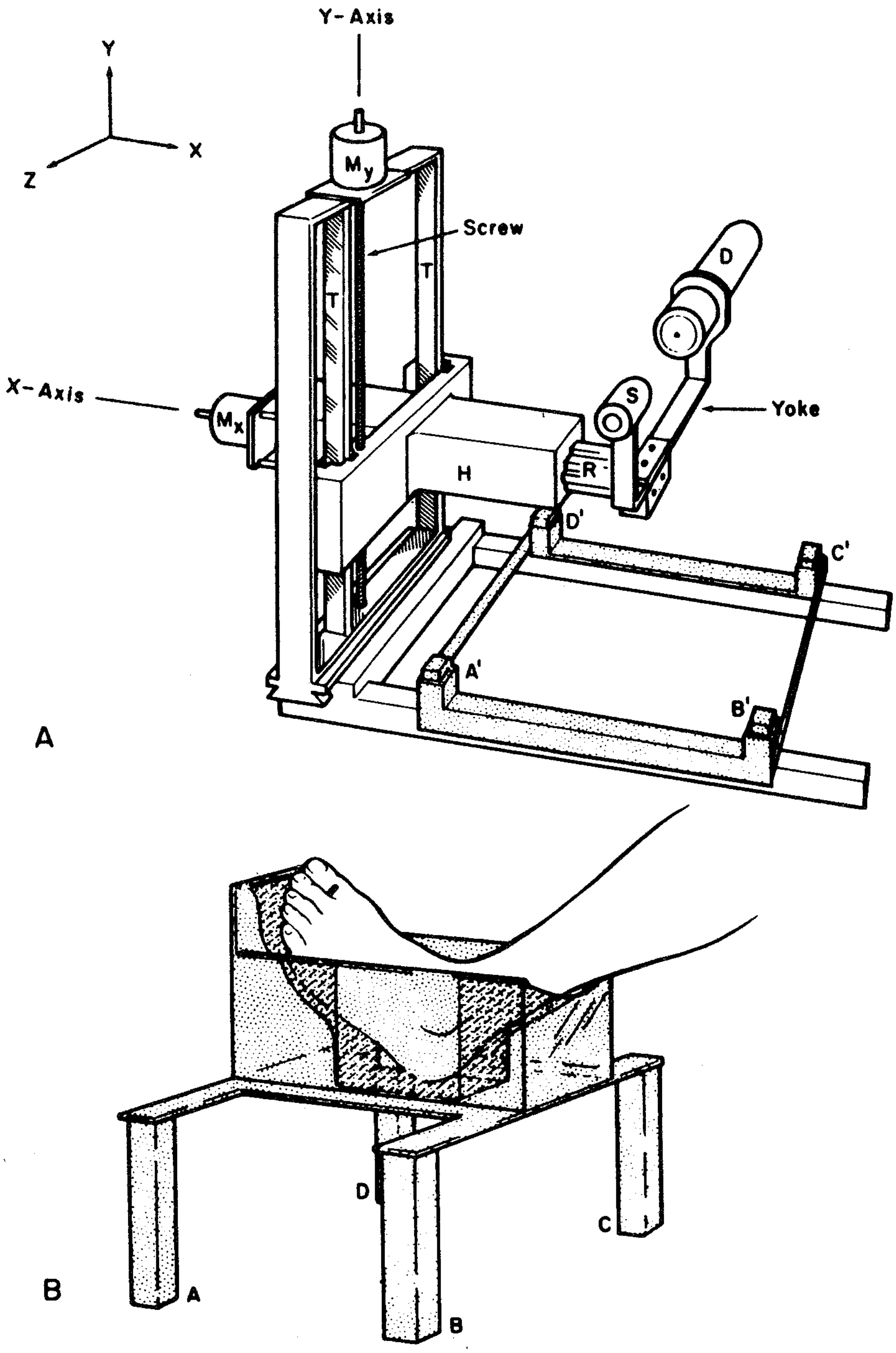

Figure 1. Scanning apparatus in the heel scanning configuration. Foot rests in a Plexiglas® box containing water as a tissue equivalent. Plastic box and holder is placed between source S and detector D on corresponding points A'B'C'D'.

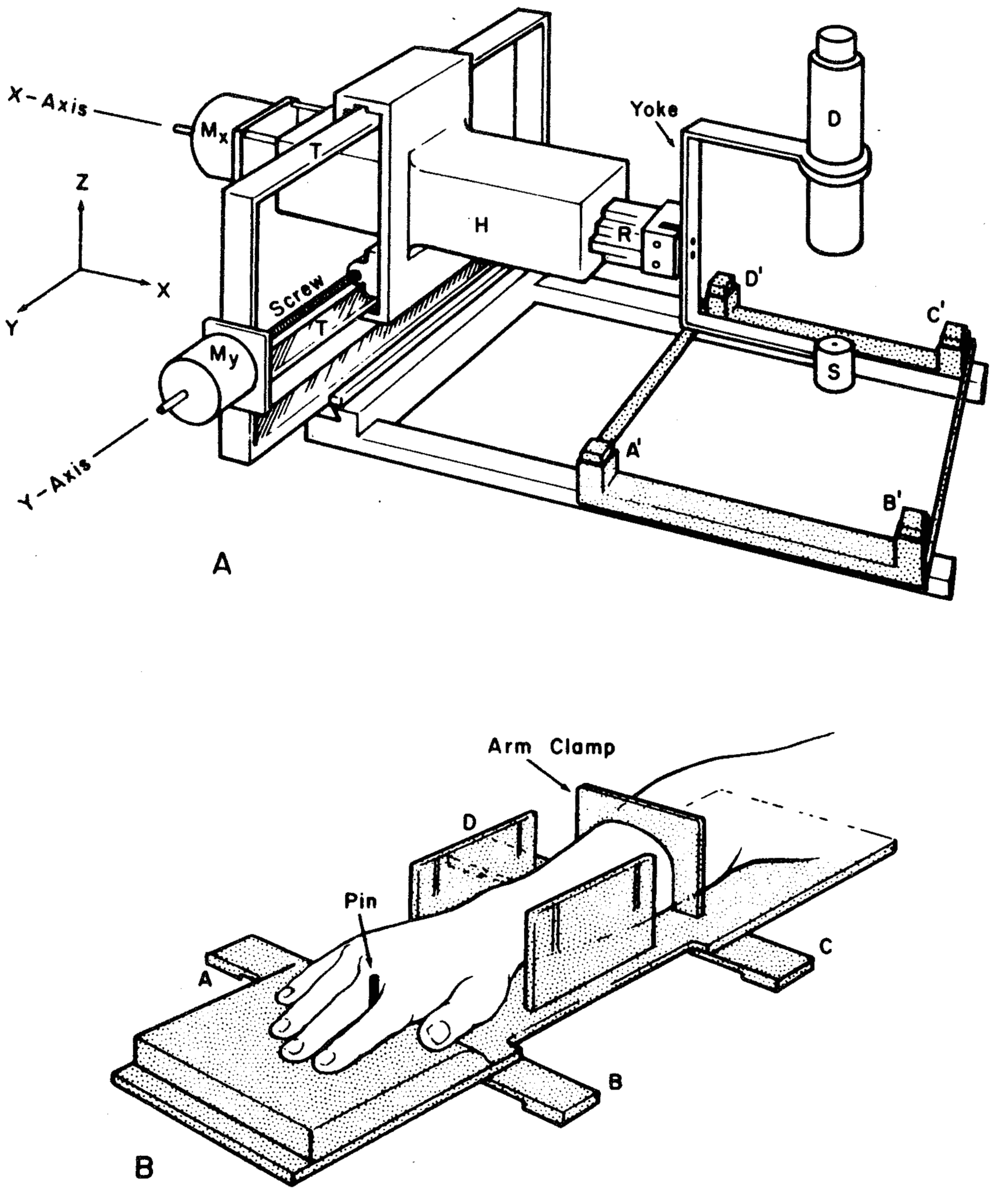

Figure 2. Scanning apparatus in the arm scanning configuration. Arm rests on a holder between two uprights and is encased in Superstuff®, a tissue equivalent material. Arm holder is placed between source S and detector D on corresponding points A'B'C'D'.

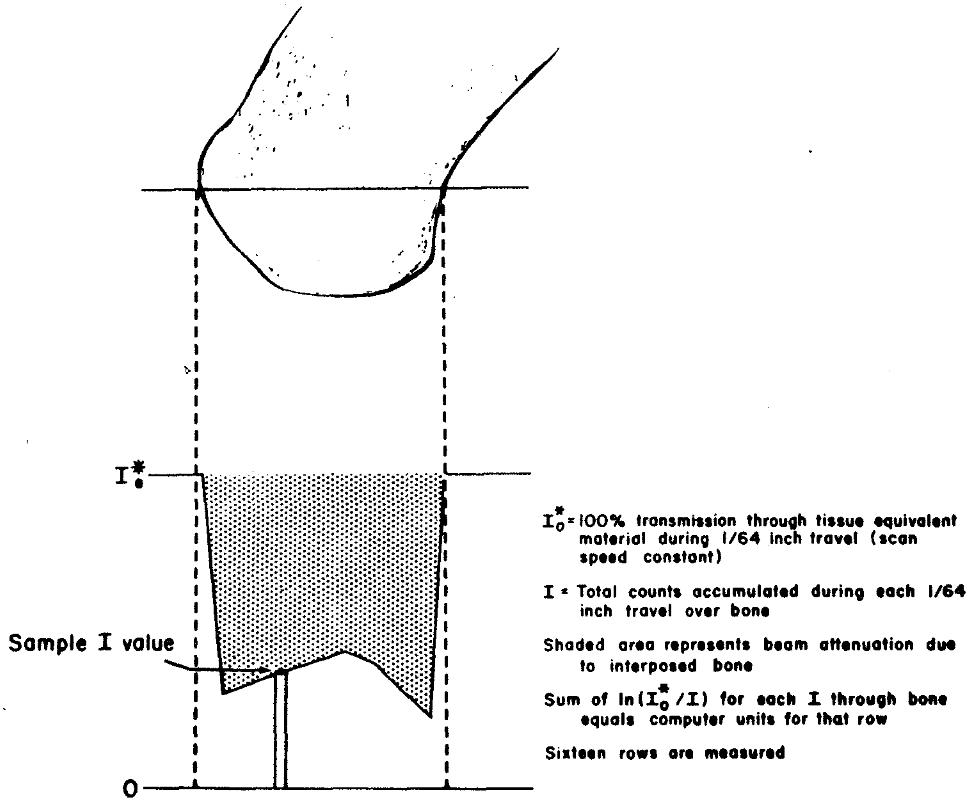

Figure 3. Method of computing mineral content.

The entire system is calibrated before and after each subject scan by measuring a Witt-Cameron standard (3) which consists of three chambers containing dipotassium hydrogen phosphate to simulate bone attenuation and a hydroxyapatite step wedge (4), (fig 4).

This technique, in addition to careful calcium balance studies, was applied to the study of 15 young male volunteers during bedrest periods of 24 to 36 weeks duration. The following observations were made.

- Prolonged bedrest can result in significant mineral losses in the central *os calcis* (fig. 5). Losses up to 40 percent have been observed. This bone is both highly trabecular as well as weight bearing. In contrast, the radius, a primarily cortical and non-weight-bearing bone, has failed to exhibit mineral losses during periods of up to 30 weeks of bedrest.

- The mean rate of whole body calcium loss was about 0.5 percent per month. Urinary calcium increased approximately 100 milligrams per day greater than the basal value, (fig. 6). A similar pattern occurred in the calcium balance. The losses reached 200 to 300 milligrams per day by the fifth to eighth week and persisted throughout the bedrest period (5), (fig. 7).

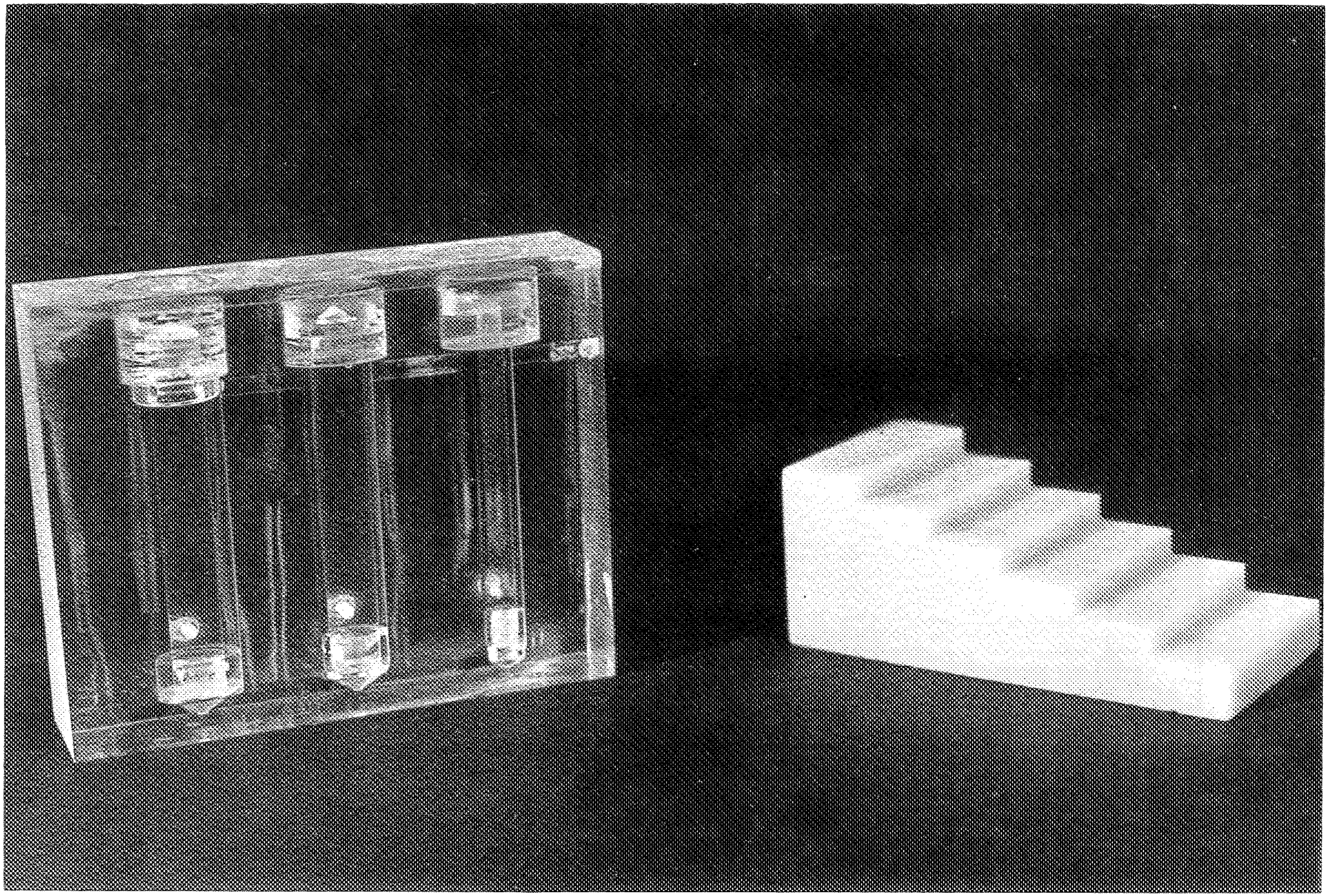

Figure 4. Standards. Witt-Cameron standard on the left and hydroxyapatite step wedge on the right.

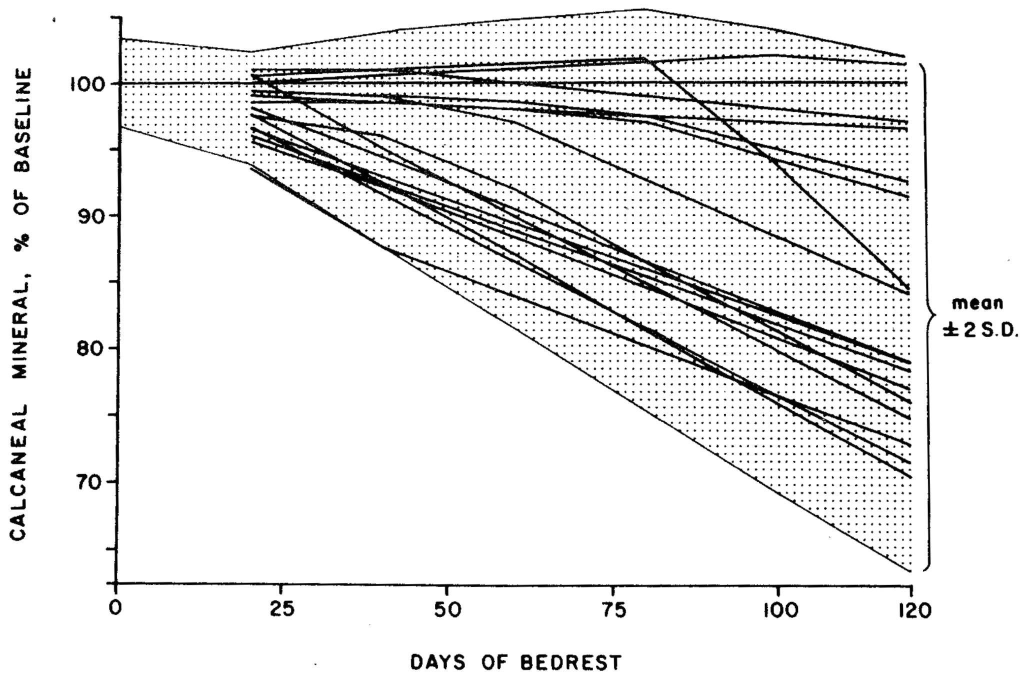

Figure 5. Calcaneal mineral loss during bedrest.

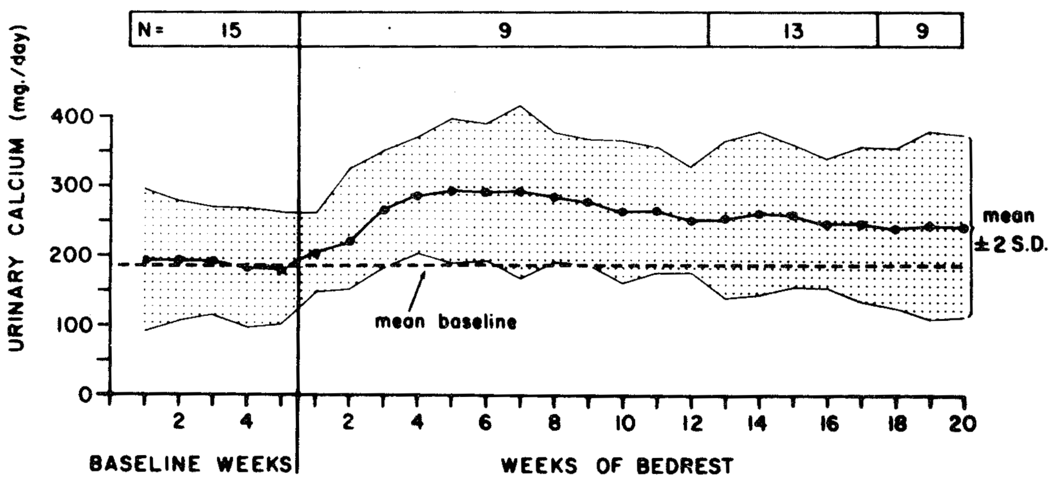

Figure 6. Hypercalciuria during bedrest without treatment.

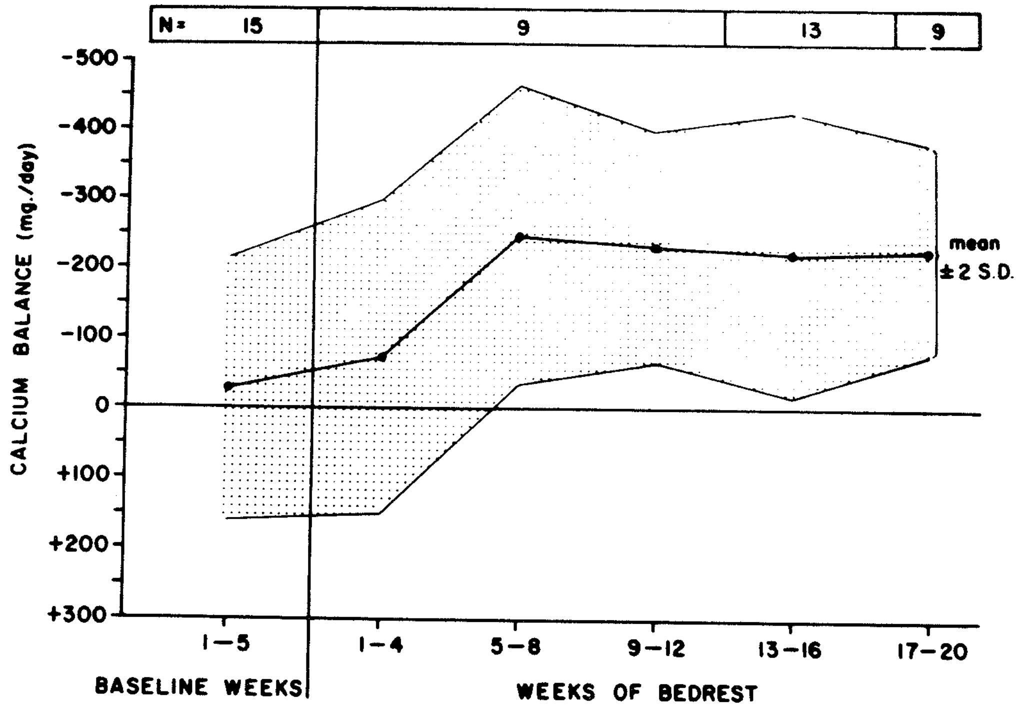

Figure 7. Negative calcium balance during bedrest without treatment.

° Little or no *os calcis* mineral loss was observed during the first month of bedrest, *i.e.*, a mean of -2.6 percent with ±2.7 percent Standard Deviation (table I). Mineral loss thereafter averaged about 5 percent per month. The two-month mean losses in fifteen subjects was -7.0 percent with one Standard Deviation limits of -1.5 to -12.5 percent. At approximately three months, the mean loss increased to 11.2 percent ±7 percent.

This wide variability of data was reconciled when it was observed that the loss could be correlated with the initial 24-hour urinary hydroxyproline excretion and the initial *os calcis* bone mineral content. We postulated that persons with a high calcaneal mineral content and/or a low urinary hydroxyproline excretion rate would be likely to retain more mineral during bed rest. Thus, the calcaneal mineral which remains at any time during bedrest would be a function of the baseline calcaneal mineral divided by urinary hydroxyproline (corrected for creatinine excretion). We will refer to this as the prediction term. The prediction term appropriate to each of these subjects is given in table I.

TABLE I. *OS CALCIS* MINERAL

15 Bedrest Subjects

Percent Change From Mean Baseline

Subject	Prediction Term	28 Days	59 Days	84 Days
1	11.2	-3.1%	- 9.3	-15.1
2	13.7	-3.9	- 9.7	-14.1
3	14.1	-8.6	-17.5	-23.1
4	14.8	-3.7	-10.9	-17.5
5	16.3	-5.2	-12.9	-19.4
6	18.0	-4.2	- 9.3	-13.6
7	20.5	-4.2	-11.0	-16.3
8	20.8	-3.3	- 8.7	-14.1
9	21.7	-0.4	- 2.0	- 4.0
10	23.7	-0.1	- 3.5	- 8.2
11	25.7	-0.3	- 1.5	- 3.4
12	28.1	-3.6	- 8.8	-14.8
13	29.7	+0.1	+ 0.6	+ 0.9
14	30.5	+2.3	+ 2.2	- 1.9
15	36.3	-0.9	- 2.5	- 3.5
Mean		-2.6%	- 7.0	-11.2
±S.D.		±2.7%	± 5.5	± 7.3

When the prediction term for each subject is plotted against the mineral losses observed, a series of regression lines were derived which can be used to estimate potential mineral losses for any subject whose prediction term has been determined, (fig. 8). It can be seen that a high prediction term is associated with little *os calcis* mineral loss and a low prediction term is associated with larger losses.

Having established these bone mineral loss profiles for simulated weightlessness here on Earth we then applied our technique to the estimation of mineral content change in the distal right radius and ulna and the central left *os calcis* of the nine Skylab crewmen. Measurements were carried out preflight at about 30, 15 and 5 days before launch and on recovery day and days 1 and 7 postflight, and at variable times thereafter. The crew of Skylab 2 and Skylab 3 were studied until each had returned to baseline. The Skylab 4 crew study had to be terminated before two of the crewmen had returned to baseline levels. A series of control subject measurements were also made in parallel with the crew. Seven subjects were studied during Skylab 2 and Skylab 4 and six during Skylab 3.

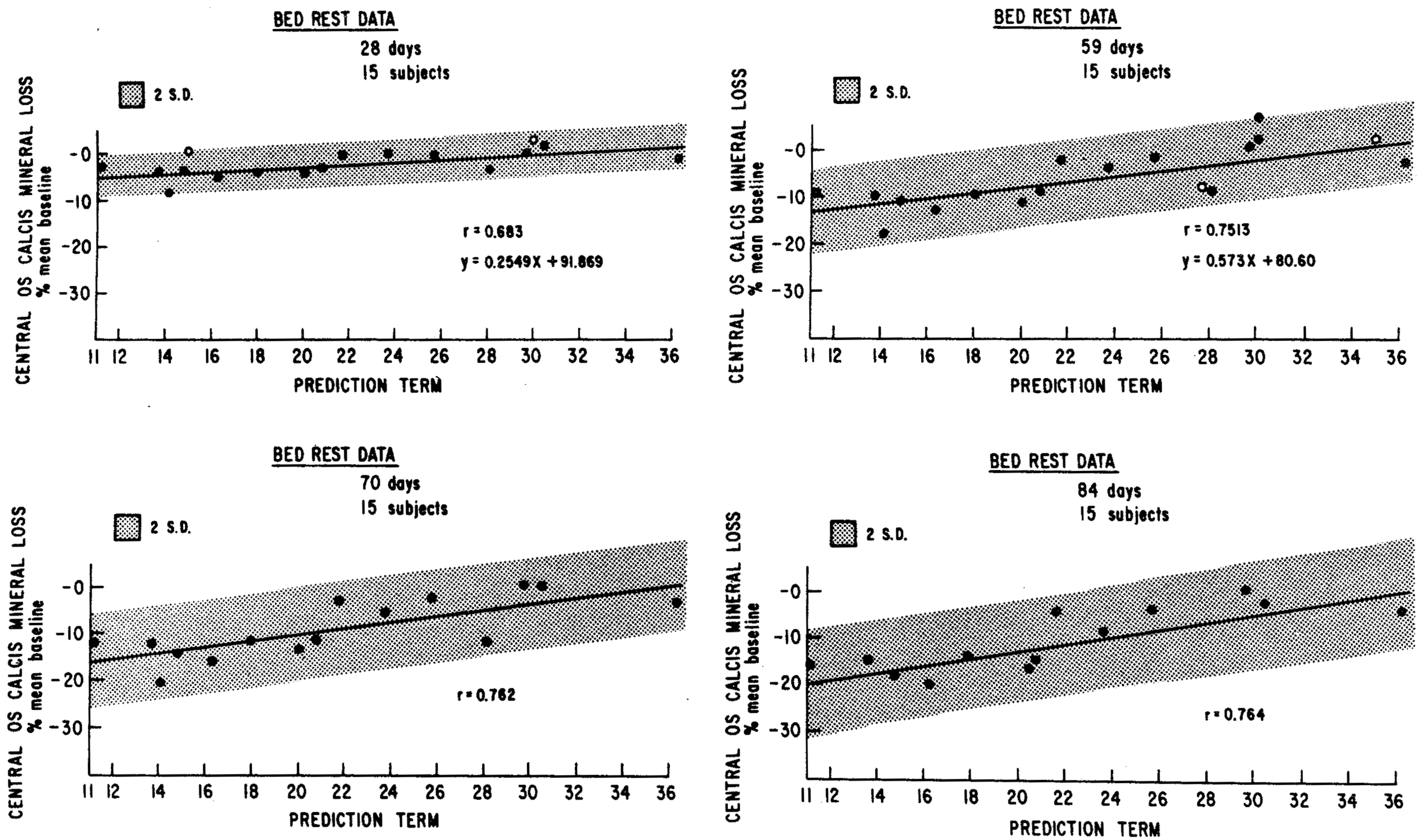

Figure 8. *Os calcis* mineral loss for varying prediction terms during 28, 59, 70 and 84 days of bedrest.

RESULTS

The mineral content changes for the Skylab crewmen are given in table II and the controls in table III. When the values for crew and controls are compared, it is clear that no losses were observed in either the radius or ulna and that loss of *os calcis* mineral was observed only in the Scientist Pilot of Skylab 3 and the Scientist Pilot and Pilot of Skylab 4. The Scientist Pilot of Skylab 3 had regained his *os calcis* mineral by day 87 postflight whereas the Scientist Pilot and Pilot of Skylab 4 had not returned to preflight levels by day 95 postflight.

TABLE II. SKYLAB CREWMEN BONE MINERAL DATA

Postflight* Percent of Mean Baseline

MISSION, DURATION	CREWMAN	LEFT *OS CALCIS*	RIGHT RADIUS	RIGHT ULNA
Skylab 2	Commander	+0.5	-0.5	-0.9
28 Days	Scientist Pilot	-0.9	+1.4	+1.9
	Pilot	+2.7	+0.2	+3.1
Skylab 3	Commander	+2.3	-1.4	+0.4
59 Days	Scientist Pilot	-7.4	+0.2	-1.6
	Pilot	+1.4	-1.6	-0.4
Skylab 4	Commander	+0.7	-1.1	-1.7
84 Days	Scientist Pilot	-4.5	+1.0	0.0
	Pilot	-7.9	-0.6	+1.4

*Skylab 2 and Skylab 3: recovery day
Skylab 4 : day 1 postflight

The losses observed generally followed the loss patterns observed in the heterogeneous group of bedrested subjects. The prediction terms for four of the Skylab 2 and Skylab 3 crewmen fell within the limits observed in the bedrested subjects and mineral loss was predicted and seen only in the Scientist Pilot of Skylab 3, (open circles in fig. 8). The two crewmen who had higher prediction terms did not lose mineral. The Skylab 4 crew had high prediction terms outside of the limits set by the bedrest experience and therefore predictions for this crew

TABLE III. CONTROLS

Bone Mineral

Post Flight Percent of Mean Baseline

Mission	Skylab 2	Skylab 3	Skylab 4
Days	28	59	84
	LEFT *OS CALCIS*		
CA	+1.2%	+2.1	+1.5
SB	+1.6	+2.0	+2.1
JH	-	-	+2.2
FK	-	-0.2	-
CLP	+2.3	+0.7	+0.7
CR	+2.4	-	-
AS	-	-	-1.3
JU	+0.2	-	-
JV	-1.7	-0.2	+0.9
MW	-0.7	+1.8	+0.6
Mean ± SD	+0.8±1.6	+1.0±1.1	+1.0±1.2
	RIGHT RADIUS		
CA	-2.2%	+0.9	-2.9*
SB	-0.8	+0.4	+0.5
JH	-	-	+0.8
FK	-	-0.8	-
CLP	-0.4	-0.3	-0.4
CR	-0.4	-	-
AS	-	-	-0.7
JU	0.0	-	-
JV	+0.6	+0.9	-1.2
MW	-0.7	-0.8	-0.5
Mean ± SD	-0.6±0.9	+0.1±0.8	-0.6±1.2
	RIGHT ULNA		
CA	-2.1%	-2.1	-3.2*
SB	+0.8	-2.4	-1.1
JH	-	-	+1.1
FK	-	-2.2	-
CLP	-0.6	+1.6	+0.2
CR	+0.5	-	-
AS	-	-	+0.7
JU	-0.8	-	-
JV	+2.8	-0.2	-0.6
MW	+0.7	-3.5	-2.0
Mean ± SD	+0.2±1.5	-1.5±1.8	-0.7±1.5

*Arm in plaster for short period during the mission.

based upon the bedrested data was not possible, (table IV). It was expected, however, that losses in the *os calcis* would not exceed 5 percent. The 7.9 percent loss seen in the Pilot cannot be explained on this basis.

TABLE IV. SKYLAB CREWS

Prediction Terms*

	Skylab 2	Skylab 3	Skylab 4
Commander	15.0	35.3	38.7
Scientist Pilot	41.6	27.7	51.5
Pilot	30.0	54.9	44.3

$* \dfrac{\text{mean preflight } os\ calcis\ mineral \text{ (mg/cm}^2\text{)}}{\text{mean preflight urinary hydroxyproline/g creatinine}}$

DISCUSSION

Based upon all of this data we have the following evidence that the bedrest situation is a closer approximation of the flight situation with regard to bone mineral than heretofore suspected.

- Calcium balances are similar for a 30 day period with 0.3 percent being lost on the first Skylab mission and 0.5 percent being lost during a comparable period of bed rest.
- Mineral loss from the *os calcis* was not evident during the 28 days of the first Skylab mission, nor after a similar period of bed rest.
- Mineral losses from the *os calcis* during the 59 day mission fell within the limits set by the bedrest experience, *i.e.*, -7.0 ± 5.5 percent.
- Mineral losses from the *os calcis* during the 84 day mission fell within the limits set by the bedrest experience, *i.e.*, -11.2 ± 7.3 percent.
- In neither situation were mineral losses seen in the radius or ulna.

- Of the nine crewmen studied, only four had prediction terms within the range of the bedrested subjects. The *os calcis* mineral changes observed in these four crewmen fell within the predicted limits.

- During Skylab 3 the Scientist Pilot doubled his urinary calcium whereas the Commander and Pilot only increased 50 percent of preflight level. Only the Scientist Pilot had *os calcis* mineral loss.

- During Skylab 4 urinary calcium more than doubled during flight in the Pilot, increased by 65 percent in the Scientist Pilot and increased by 60 percent in the Commander. *Os calcis* mineral losses occurred in the same order, *i.e.*, greatest in the Pilot.

CONCLUSIONS

It is concluded that mineral losses do occur from the bones of the lower extremities during missions of up to 84 days and that in general they follow the loss patterns of the bedrested situation. The levels of loss observed in the Skylab crews have been of no clinical concern. A prediction term has been proposed in an attempt to translate bedrest data into the weightless condition. In general, this had been applicable to weightlessness in all crewmen whose prediction term fell within the limits set by the bed rest study.

ACKNOWLEDGEMENT

The support of John Ullmann, Scott Brown, Fred Kolb and Alan Silverstein in the performance of the measurements and the support of Dr. Victor Schneider and the metabolic unit laboratory staff of the U.S.P.H.S. Hospital, San Francisco, is gratefully acknowledged.

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MUSCULAR DECONDITIONING AND ITS PREVENTION IN SPACE FLIGHT

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ABSTRACT

Under weightlessness without countermeasures, a rapid disuse atrophy of weight-bearing muscular groups appears to occur. For the Skylab Program, such losses were measured with a constant speed (isokinetic) dynamometer. Ten maximum-effort, full-range flexion/extensions of the elbow and hip/knee at 45 degrees/second were recorded and evaluated for each crewman before and after flight. Anthropometric measurements allowed computation of volume changes of limb segments.

During the Skylab 2 mission (28 days), a bicycle ergometer and an isometric device were used for exercise. Losses of strength and of muscle mass, especially in leg antigravity groups, were such that additional exercise devices were launched and exercise time was sharply increased on the Skylab 3 mission (59 days). Good arm exercises and acceptable trunk exercises were provided, but loads and types of leg exercise were limited. This imbalance was reflected after flight by the lack of measurable loss in arm function. Leg function and muscle mass had improved relatively over the Skylab 2 mission, but large decreases continued to be apparent. In addition to the other devices, a simulated treadmill consisting of a Teflon® walking surface, a harness, and elastic bungees to provide 170 pounds equivalent weight was used daily throughout the Skylab 4 mission (84 days). This flight crew returned in unexpectedly good condition; slight losses in muscle functions of arms or legs were measured.

Although weightlessness could cause rapid atrophy of many major muscle groups and disability on return to normal gravity could result after long missions, it has been demonstrated that such deconditioning can be prevented relatively easily through use of familiar exercise techniques. Future research efforts should focus on optimum methods of exercise with respect to crew time and crew acceptance, interrelationship of musculoskeletal fitness with cardiovascular fitness, and design of practical, efficient, total body exercisers.

INTRODUCTION

A major portion of man's musculoskeletal system is dedicated to supporting and moving his body against Earth's gravity. This mass of muscle places heavy requirements for support on other body systems. For example, maximum capacity of the cardiovascular and respiratory systems, and to a large measure their condition, is a function of demands from the body's musculature. It is a common experience that removal of muscle stresses under one-g, that is, lack of suitable exercise, results in atrophy of both muscle and its supporting systems. It could be confidently predicted that atrophy would occur rapidly under weightlessness unless suitable exercise was provided.

The time taken for such atrophy to occur allowed short missions such as Apollo to proceed without significant problems. But it was no longer possible to consider a long mission like Skylab without

° some method of evaluating muscle condition, and

° suitable in-flight exercise.

On Skylab, we instituted first a minimum impact muscle function test, and as the mission demanded, added exercise and exercise devices and expanded the testing. The result was a different exercise environment on each flight, such that we had three experiments, with the results of each flight affecting the next. The flights will be described chronologically. This report will, insofar as possible, address only aspects of skeletal muscle since the cardiovascular aspects of conditioning and use of the bicycle ergometer are covered in another experiment.

PROCEDURE

Evaluation of the right arm and leg was done preflight and postflight on all missions with the Cybex Isokinetic Dynamometer. This dynamometer may be rotated in either direction without resistance until an adjustable limit speed is reached. Speed cannot be increased above this limit by forces of any magnitude, that is, the constant speed-maximum force of isokinesis is achieved. Input or muscle forces are continuously recorded. Various arms, handles, and the like may be attached to the dynamometer to couple any desired segment of the body to the machine.

The arrangement used on Skylab is shown in figure 1. A crewman, after thorough warm up, made 10 maximum effort full flexions and extensions of the arm at the elbow and of the hip and knee at an angular rate of 45 degrees per second.

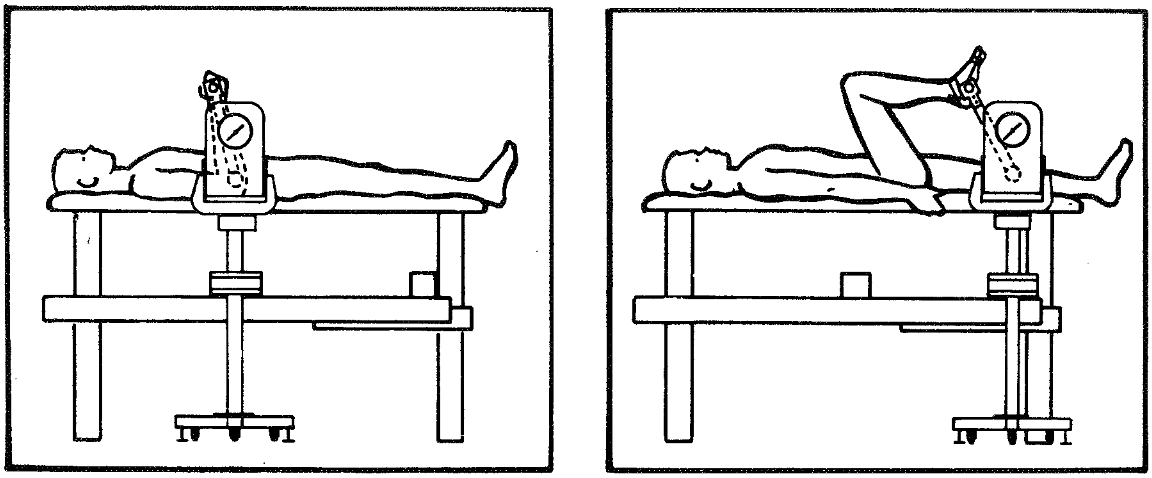

Figure 1. Test arrangement, Cybex Isokinetic Dynamometer.

A continuous force record was made of each repetition at a rate of 25 millimeters per second and the integral of force, or under these conditions, work is recorded on a second channel (fig. 2).

Machine errors are small, two to three percent or less. The test gives a measurement of strength comparable to the more commonly used isometric testing, but has the great advantage of recording this force throughout the whole range of motion as well as allowing a number of repetitions for statistical purposes. It is sensitive enough to show small changes in performance which may occur in days.

A great deal of information is contained in the recordings made, but only one quantity will be used here - the peak force of each repetition at the same point in the cycle. Use of a single point on the tension curve to represent the entire curve may be open to criticism, especially in the leg where a number of muscles are involved. However, for the purposes here, I feel this is a valid measure of strength of the muscles tested.

A plot of such peak points from a preflight and postflight curve is shown in figure 3. The strength for a given movement is taken as the average of 10 repetitions. As you can see, a fatigue decrement is present and may vary. It is included in the strength figure by virtue of averaging the 10 repetitions.

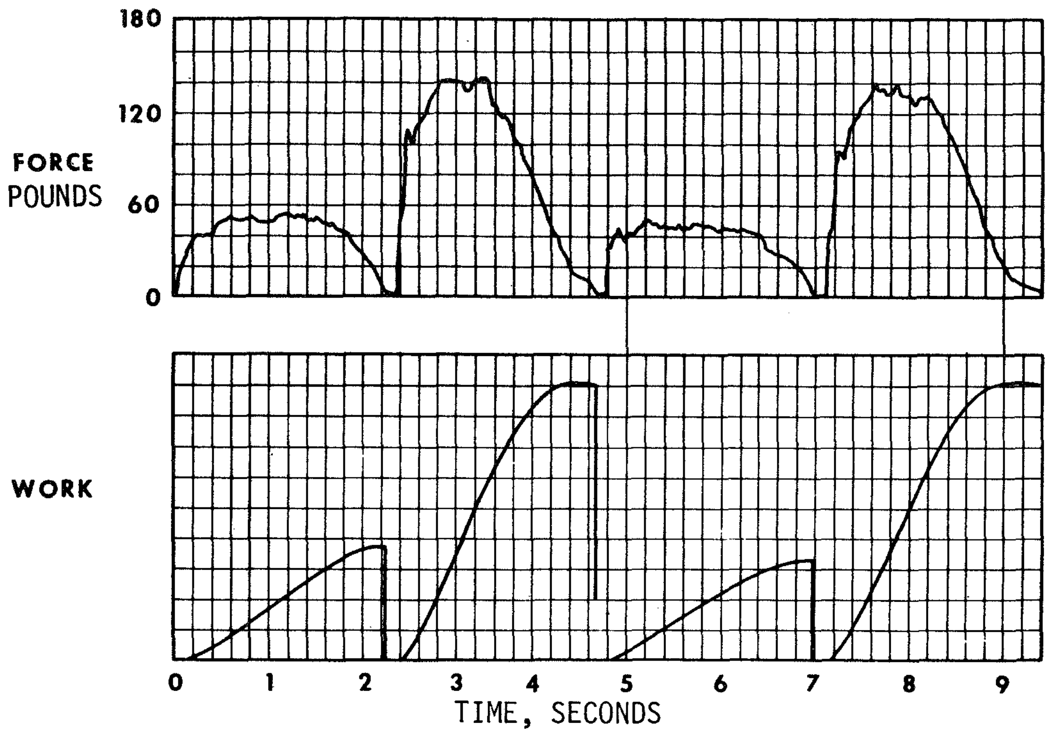

Figure 2. Recording of muscle forces, right leg, Skylab 3 Backup Pilot.

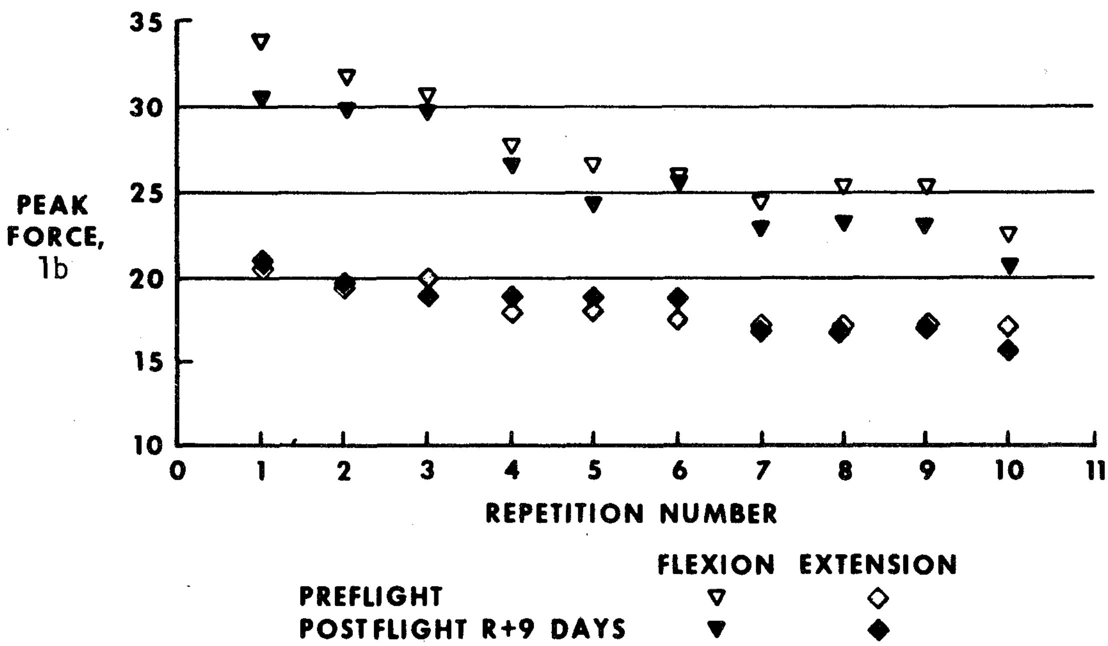

Figure 3. Peak arm forces preflight and postflight, Skylab 3 Commander.

On Skylab 2 only the bicycle ergometer was used for in-flight exercise. Pete Conrad used it in the normal fashion and was the only person on Skylab to use it in the hand-pedal mode and also the only person on this crew to exercise at rates comparable to those of later missions.

On Skylab 3, testing was performed 18 days before launch and five days postflight. It was recognized that this was too far removed from the flight, but this was the best that could be done under schedule constraints.

By the time muscle testing was done on day 5, there had been a significant recovery in function; however, a marked decrement remained. Results from Skylab 2 will be shown in a moment in conjunction with the results from Skylab 3. The decrement in leg extensor strength approached 25 percent, while the arms had suffered less but also had marked losses. The Commander's arm extensors had no loss, since he used these muscles in hand-pedalling the bicycle. This illustrates a crucial point in muscle conditioning: to maintain the strength of a muscle, it must be stressed to or near the level at which it will have to function. Leg extensor muscles which support us in standing and propel us in walking must develop forces of hundreds-of-pounds, while the arm extensor forces are measured in tens-of-pounds. Forces developed in pedalling the bicycle ergometer are typically tens-of-pounds and are totally incapable of maintaining leg strength. The bicycle ergometer is an excellent machine for aerobic exercise and cardiovascular conditioning, but it simply cannot develop either the type or level of forces to maintain strength for walking under one-g.

Immediately after Skylab 2, work was started on devices to provide adequate exercise to arms, trunk, and legs. A mass-produced commercial device, called Mini Gym, was extensively modified and designated "MK I". A centrifugal brake arrangement approximated isokinetic action on this device.

Only exercises which primarily benefitted arms and trunk were available as shown in figure 4. Forces transmitted to the legs were higher than those from the ergometer, but they were still limited to an inadequate level, since this level could not exceed the maximum strength of the arms which is a fraction of leg strength.

A second device, designated "MK II", consisted of a pair of handles between which up to five extension springs could be attached, allowing maximum forces of 25 pounds per foot of extension to be developed.

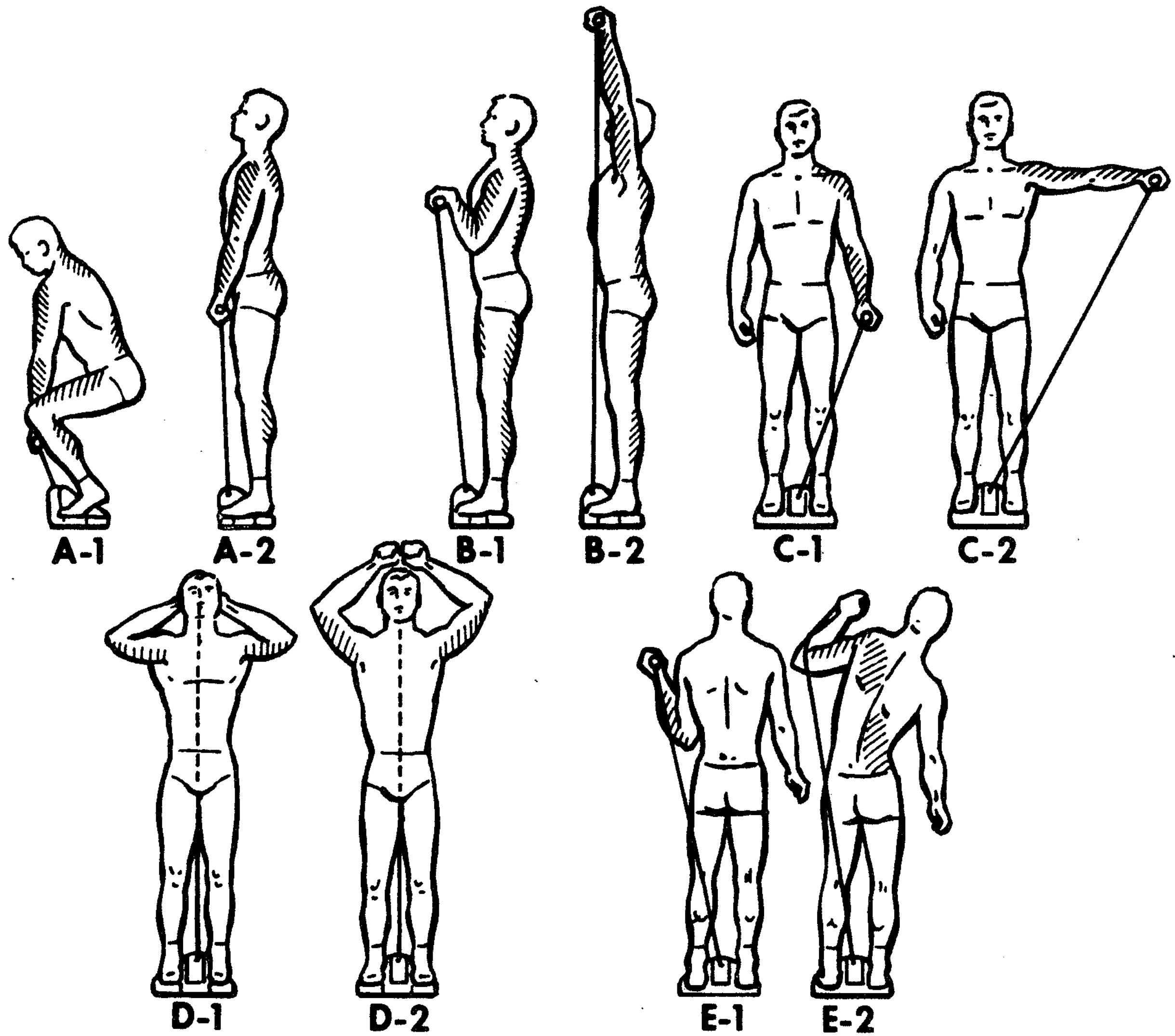

Figure 4. MK I exerciser positions.

These two devices were flown on Skylab 3, and food and time for exercise was increased in-flight. The crew performed many repetitions per day of their favorite maneuvers on the "MK I" and to a lesser extent, the "MK II". Also, the average amount of work done on the bicycle ergometer was more than doubled on Skylab 3 with all crewmen participating actively.

Results of muscle testing of Skylab 3 crewmen demonstrated marked differences from the Skylab 2 crew.

Looking at changes in arm forces on Skylab 3, one sees complete preservation of flexor function in contrast to Skylab 2 (fig. 5). The Scientist Pilot showed a marked gain in arm strength. This is the result of putting a good distance runner, which Owen is, on the equivalent of a weightlifting program.

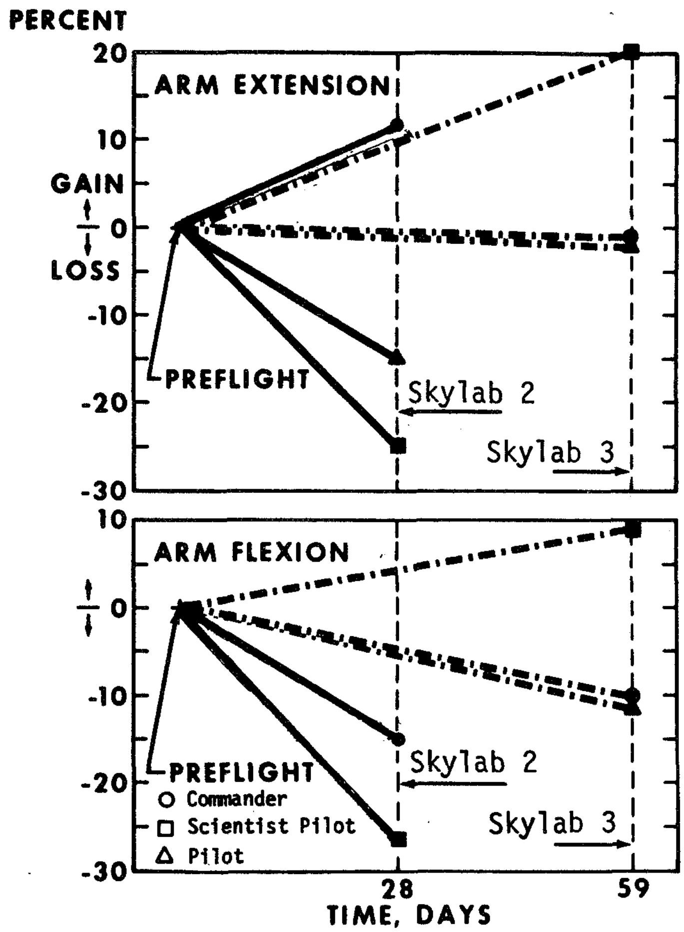

Figure 5. Changes in arm forces on Skylab 2 and Skylab 3.

Looking now at leg function in figure 6, we see a different picture. Only two Skylab 3 crewmen are shown since the Commander suffered a recurrence of a back strain from a lurch resulting from a roll of the recovery ship - possibly another demonstration of the hazard of muscle deconditioning.

Although there is a relative improvement or less loss over Skylab 2, there nevertheless remains a significant reduction in muscle strength. It seems rather obvious that the "MK I" and "MK II" exercise devices did a good job in arm preservation but were still inadequate to maintain leg function.

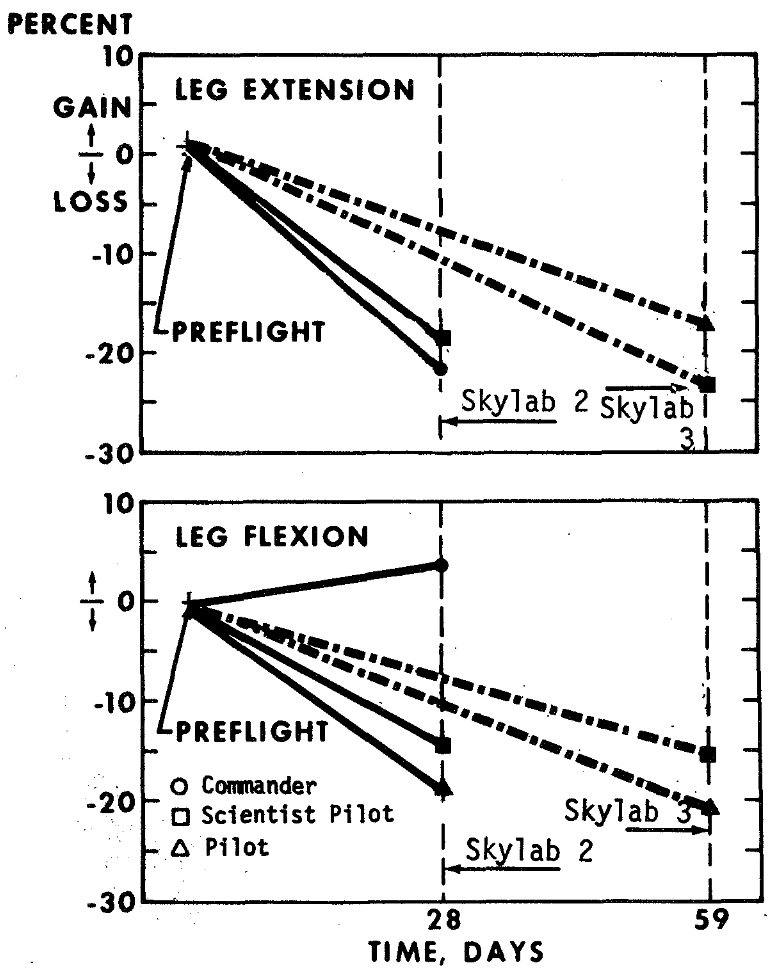

Figure 6. Changes in leg forces on Skylab 2 and Skylab 3.

Some device which allowed walking and running under forces equivalent to gravity appeared to be the ideal answer to this problem. This had long been recognized and immediately after Skylab 2, work was started on a treadmill for Skylab 4. As the mission progressed, launch weight of Skylab 4 became crucial such that the final design was simulation of a treadmill in response to the weight constraints. The final weight for the device was 3-1/2 pounds.

The treadmill, shown in figure 7, consisted of an aluminum Teflon® walking surface attached to the iso-grid floor. Four rubber bungees providing an equivalent weight of 175 pounds (80 kg) were attached to a shoulder and waist harness. By angling the bungees, an equivalent to a slippery hill is presented to the subject who must climb it. High loads were placed on some leg muscles, especially in the calf, and fatigue was rapid such that the device could not be used for significant aerobic work.

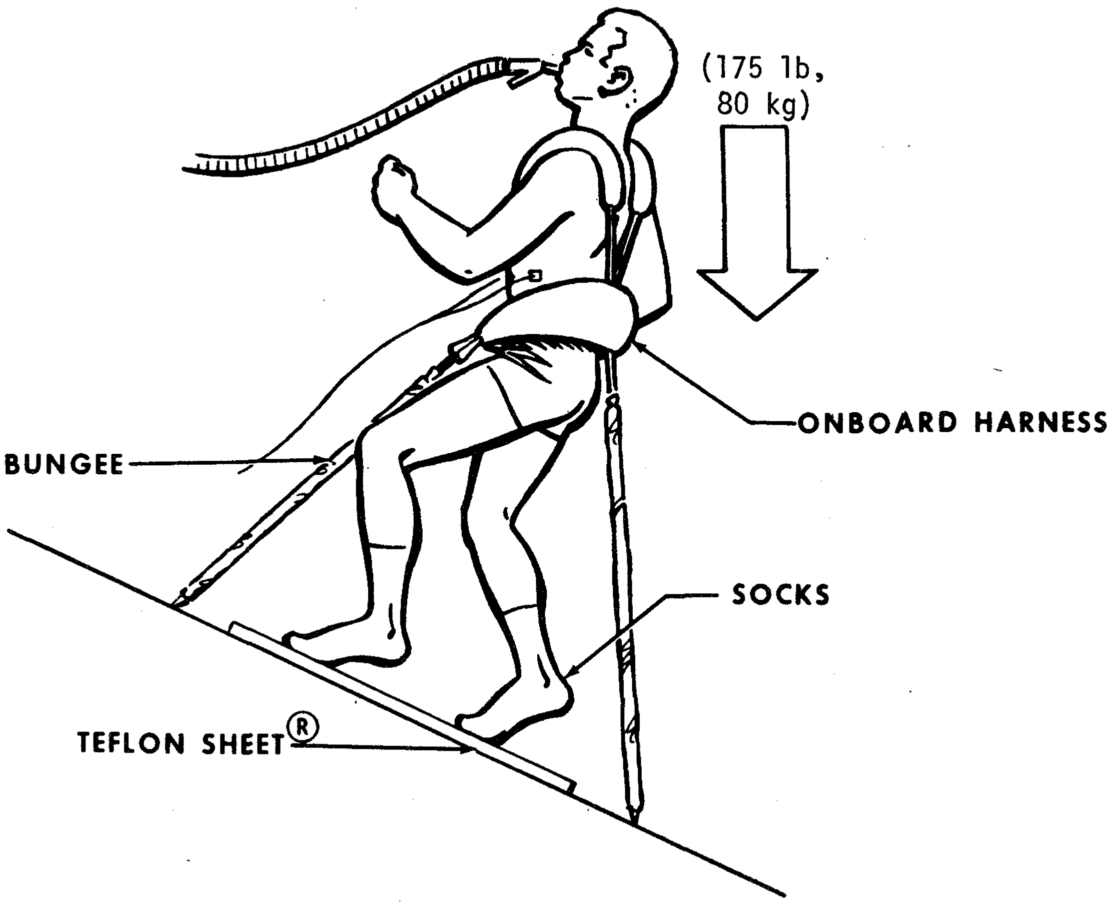

Figure 7. Treadmill arrangement.

On Skylab 4, the crew used the bicycle ergometer at essentially the same rate as Skylab 3, and the MK I and II exercisers. In addition, they typically performed ten minutes per day of walking, jumping, and jogging on the treadmill. Food intake had again been increased.

Even prior to muscle testing, it was obvious that the Skylab 4 crew was in surprisingly good condition. They stood and walked for long periods without apparent difficulty on the day after recovery in contrast to the earlier missions. Results of the testing confirmed a surprisingly small loss in leg strength after almost three months in weightlessness. A summary of the exercise and strength testing shown in averaged values for the three missions is depicted in figures 8 and 9. One point to be noted is the relatively small losses in arms as compared to legs in all missions. This is reasonable for in space ordinary work provides loads for the arms that are relatively much greater; the legs receive virtually no effective loading. With the MK I and II exercisers, arm losses were reduced to negligible values except in arm extensors on Skylab 4, most of which was accounted for by the Commander.

Size is another common measure of muscle condition, and a plot of average change in leg volume for each crew in the postflight period is shown in figure 10. Changes for the first two days must be primarily fluid. The crews of Skylab 2 and 3 lost essentially the same volume in spite of a two-fold difference in mission duration which indicates partial protection from increased ergometer work, other exercise devices and increased food on Skylab 3. The longest mission, Skylab 4, lost only one-half of the volume of the shorter ones. A second point is that Skylab 4 crewmen quickly recovered their preflight volume in contrast to the crewmen of the other two missions. Notice that this data parallels that of leg extensor strength losses which were roughly equal on Skylab 2 and 3, and sharply reduced on Skylab 4.

There was a six and one-half to nine-fold reduction in rate-of-loss of leg extensor strength, leg volume, lean body mass and total body mass from Skylab 2 to Skylab 4. One might argue that this reduction simply represents some kind of equilibrium with increasing mission duration, but this is not consistent with data shown in Table I which shows absolute losses.

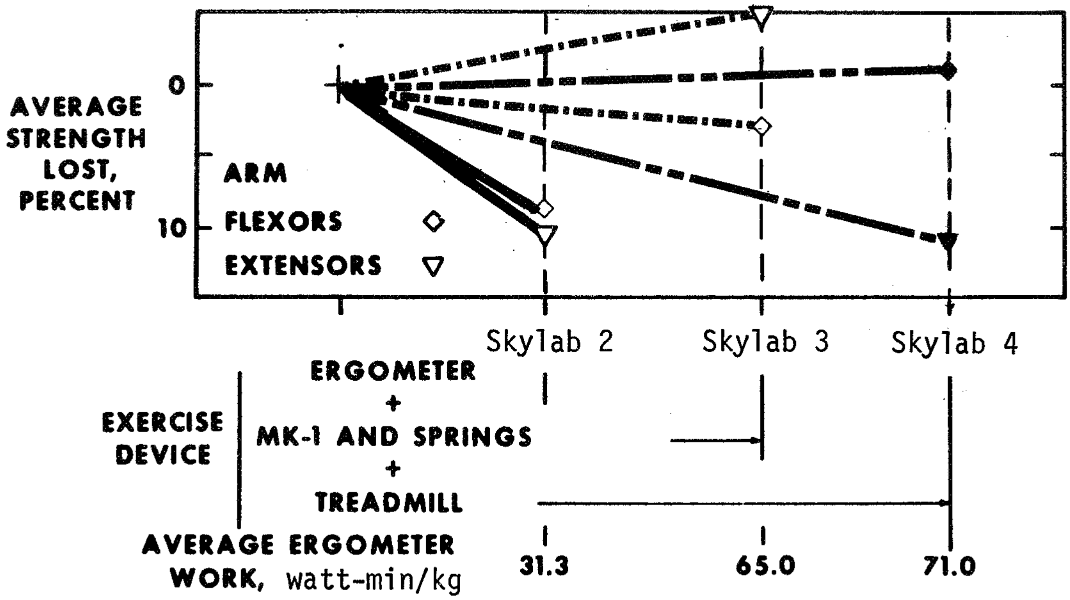

Figure 8. Average strength changes, arm.

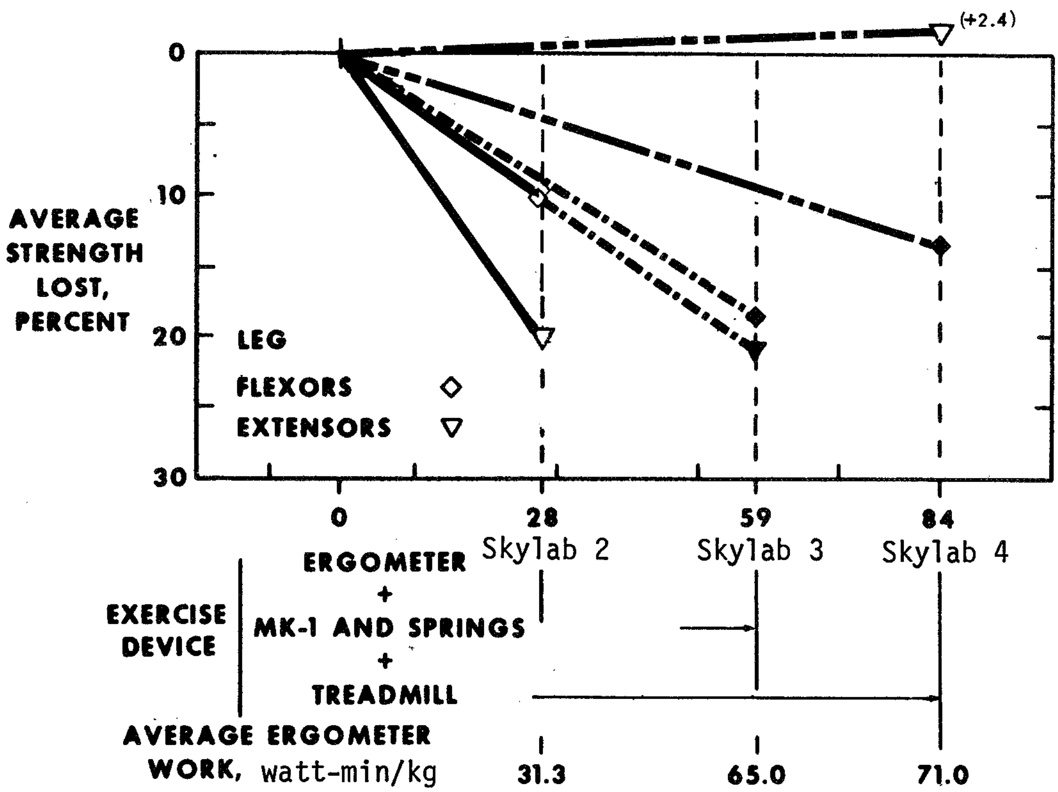

Figure 9. Average strength changes, leg.

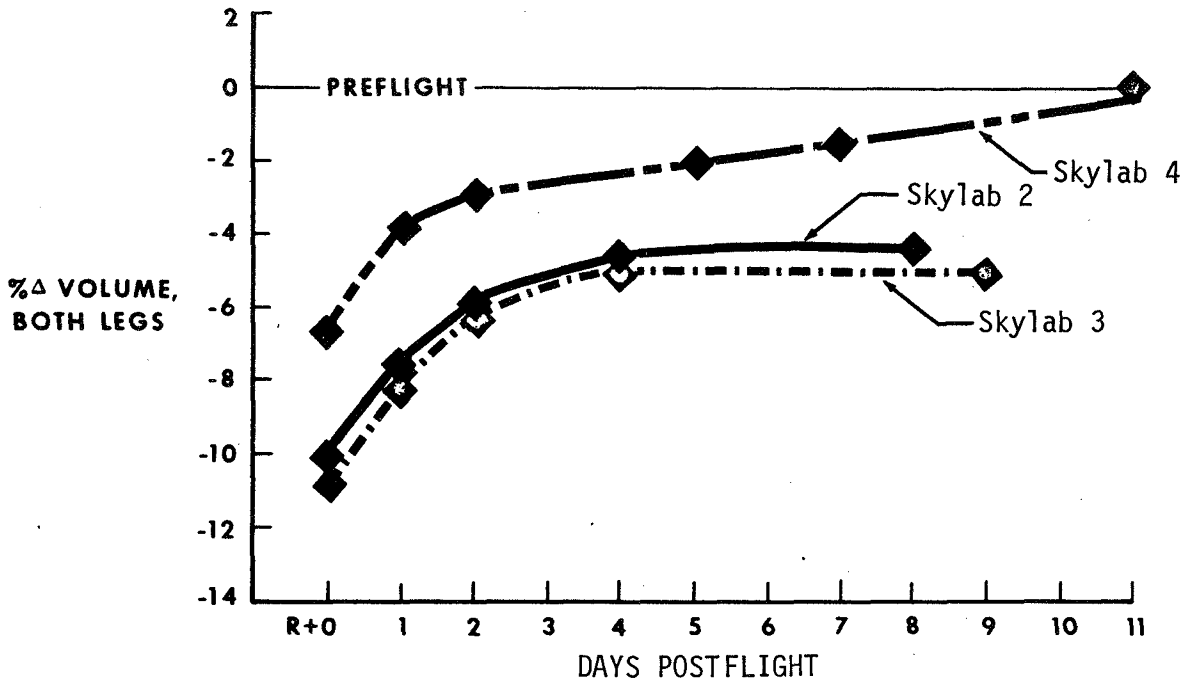

Figure 10. Average leg volume change, postflight on Skylab 4.

TABLE I. SUMMARY OF CREW AVERAGES OF EXERCISE RELATED DATA

Skylab Crew	Change In Leg Extension Forces F-15 to R+1, Percent/Day	Change In Leg Volume F-15 to R+5, Percent/Day	Change In Lean Body Mass F-15 to R+1, Percent/Day	Change in Body Weight F-1 to R+0, Percent/Day	Average Daily Ergometer Exercise/ Body Weight watt-min/kg
*2	-0.89	-0.160	-0.089	-0.13	31.3
†3	-0.44	-0.088	-0.019	-0.08	65.0
‡4	-0.09	-0.023	-0.011	-0.02	71.0

Exercise devices available

*Bicycle ergometer

†Bicycle ergometer, MK-I and MK-II exercisers

‡Bicycle ergometer, MK-I and MK-II exercisers, treadmill

As shown in figure 11, Skylab 4 shows again a marked improvement as regards weight, leg strength and leg volume. I think I am correct in attributing these reductions in loss of muscle strength and bulk to the exercise devices and exercise time that were added. There can be little doubt that adding the MK I and II improved the arm performance of the crewmen on Skylab 2 and 3; and equally little doubt that the treadmill sharply reduced loss of leg strength and mass, since there was negligible increase in leg exercise with other devices on Skylab 4.

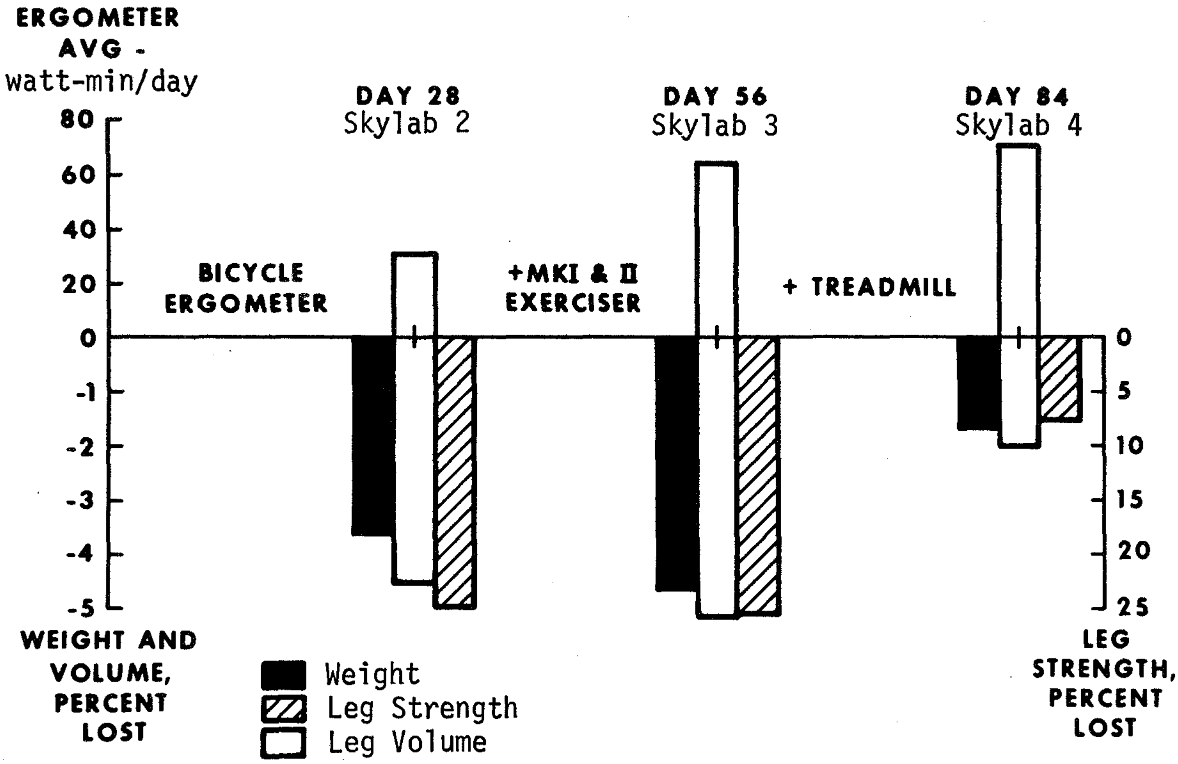

Figure 11. Exercise related quantities on Skylab missions.

However, it must be recognized that another variable was present - food. Virtually all the nutritionists that I know recognize that metabolic losses in normal subjects are mixed, *i.e.*, both fat and muscle are lost. Vanderveen and Allen[1] deliberately reduced caloric intake during a one-g chamber test simulation of space flight conditions using subjects chosen to be as equivalent as possible to the astronaut population. They found an almost pure muscle loss.

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[1]Vanderveen, J. E. and T. H. Allen. 1972. Energy Requirements of Man Living In a Weightless Environment. COSPAR, Life Sciences and Space Research X - AKADEMIE-VERLAG-BERLIN.

At this time, I cannot escape the conclusion that muscle in space is no different from muscle on Earth, if it is properly nourished and exercised at reasonable load levels, it will maintain its function.

I think that a properly designed treadmill used for considerably less than an hour a day will not only protect leg and trunk musculature, but will also provide aerobic exercise to cover the cardiorespiratory system. It will not be difficult to add arm exercise at the same time such that we meet the requirements for a single total body exerciser.

The muscle-system is rightly described as the musculoskeletal system since they are inseparable. While I would not dare comment on the Ca+ ion and its dynamics, I will say that bone-like muscle, when properly stressed and nourished, will in all probability retain its strength. Bed rest studies not withstanding, it seems entirely possible to design such stressors that are compatible with space flight.

Finally we see another system of the human body which, properly nourished and provided with a minimum of support, in this case physical stress, can adapt to weightlessness and retain its function for return to one-g.

ACKNOWLEDGEMENT

James Perrine has supported and aided this experiment to the point that he was more properly a coinvestigator. He not only invented the Cybex equipment used in testing but is also one of the original thinkers in muscle physiology and testing. Roger Nelson provided the original equipment for testing and his brother, Arthur, gave much useful aid in development of electromyography testing to be used in conjuction with the muscle test. The latter effort was aborted by unfortunate events. Jim Evans constructed the integrator and aided in instrumentation work. C. A. Samaniego aided in the testing process and Dave Hilaray of Lumex provided outstanding technical support of the Cybex gear.

Development of the treadmill was a combined effort with Bill Huber and his group and was aided by support of John Stonesifer, and the Skylab 4 crew, especially Bill Pogue.

BIOSTEREOMETRIC ANALYSIS OF BODY FORM

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ABSTRACT

Biostereometrics is the measurement and the mathematical description of the three-dimensional form of biological objects. Stereophotogrammetry was used to derive the Cartesian coordinates of numerous points on the body surface of the Skylab crewmen, both before and after flight, on all three Skylab missions. Mathematical analysis of the coordinate description allows the computation of whole body surface area and volume, as well as the volume of body segments, and the area and shape of cross sections. Loss of body weight in the first two Skylab flight crews was accompanied by comparable loss of volume and little change in density. Volume loss was divided about equally between the trunk and the legs; however, because the volume of the legs is less than that of the trunk, this finding represented a greater proportional volume loss in the legs. Comparison of cross-sectional areas suggests that the calf undergoes shrinkage to a greater extent than does the thigh. The suggested interpretation of these changes is that during flight there was a reduction in body fluid, a partial muscle atrophy, particularly in the legs, and, in all but two of the crewmen, a loss of body fat. The partial muscle atrophy probably resulted from relative disuse in the absence of gravity, and was lessened to some extent by the in-flight exercise program. The stereoscopic images of the crewmen form a permanent archival record of body form on which more detailed measurements may be made in the future when advances in analytical technique make more detailed measurement possible.

INTRODUCTION

Biostereometrics is the science of measuring, and describing in mathematical terms, the three-dimensional form of biological objects. An extensive background to the subject has been given by Herron (1972)(1). Exposure to weightlessness results in a dramatic change in the patterns of muscular activity in the human body insofar as they control posture and are responsible for locomotion. These changes in muscular activity might be expected to result in changes in the bulk of particular muscle groups, and in the overall energy consumption of the body, which,

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unless accompanied by a compensating change in food intake, would cause a change in body fat. Biostereometric analysis enables changes in muscle bulk to be measured, and by examining those areas of the body containing fat deposits, enables general conclusions to be drawn about changes in body fat.

METHOD

The biostereometric measurements of the Skylab crewmen were made by four-camera stereophotogrammetry, during the immediate preflight and postflight periods. An attempt was made during the final Skylab mission (Skylab 4) to take in-flight stereopairs of the crewmen - these photographs have not yet been analyzed. Photographs were taken of the first (Skylab 2) crew 39, 14, and 2 days prior to flight, on recovery day, and 19 days after recovery. The second (Skylab 3) crew was photographed 31, 14, and 5 days prior to flight, and 1 and 31 days after recovery. The final (Skylab 4) crew was photographed 35, 21, 10, and 6 days prior to flight, and on recovery day, and 1, 4, 30, and 68 days after recovery. The subjects were weighed within a few minutes of taking the photographs.

The layout of the apparatus is shown in figure 1. The subject stands between two control stands, which provide dimensional information in the three orthogonal axes. He is photographed simultaneously by two cameras in front, and two cameras behind. The subject is nude except for an athletic supporter, and a skullcap to press his hair down. To minimize variations in chest volume, photographs are taken in maximal forced exhalation. Between each pair of cameras is a strobe-projector, which through a focusing lens projects a pattern of lines onto the subject's skin, making it easier to visualize during the subsequent plotting process. The cameras are modified wide-angle Hasselblads using fine-grain glass plates, for dimensional stability of the image. Duplicate sets of plates are exposed to insure against breakage, or camera malfunction. The equipment is portable, and photographs were taken at Johnson Space Center, Kennedy Space Center, and on the recovery ships. After development the plates are analyzed on a stereoplotter, which derives the three-dimensional coordinates of thousands of points on the body surface, punching them on IBM cards for subsequent computer analysis. The computer program derives area, shape and perimeter of between 80 and 100 sections of different parts of the body, and volume and surface area of any segment of the body, and of the body as a whole.

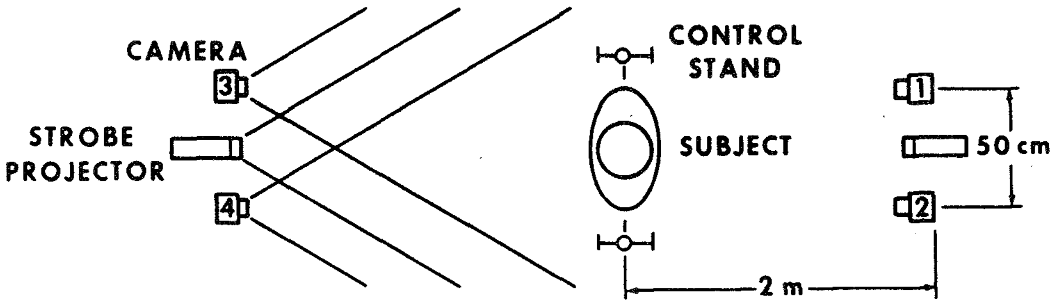

Figure 1. Layout of stereophotogrammetry.

RESULTS AND DISCUSSION

Figure 2 compares measurements of leg circumference derived from stereometric analysis with tape measure circumferences obtained on the same day (Thornton *et al.*, 1974) (2). The pattern seen in figure 2 is typical of all the comparisons which have been made between the two methods, the leg circumference measured by stereometric techniques exceeding that by the tape measure by 10 to 20 millimeters. There are two probable causes for this difference. Firstly, the stereoscopic photographs are made with the subject standing, whereas the tape measurements are made with the subject supine; the leg volume standing would exceed that supine by the volume of blood and interstitial tissue fluid brought into the leg under the influence of gravity. Secondly, stereometric analysis, being a noncontact method, does not involve the compression of tissues, however small, which results from the use of a tape measure. The 10 to 20 millimeter discrepancy between the methods represents a difference in limb volume of 250 to 500 milliliters which is entirely reasonable for the increased volume of blood and tissue fluid in the leg after transferring from the supine to standing position. These differences would in no way invalidate comparisons made at different times on a single subject using the same technique.

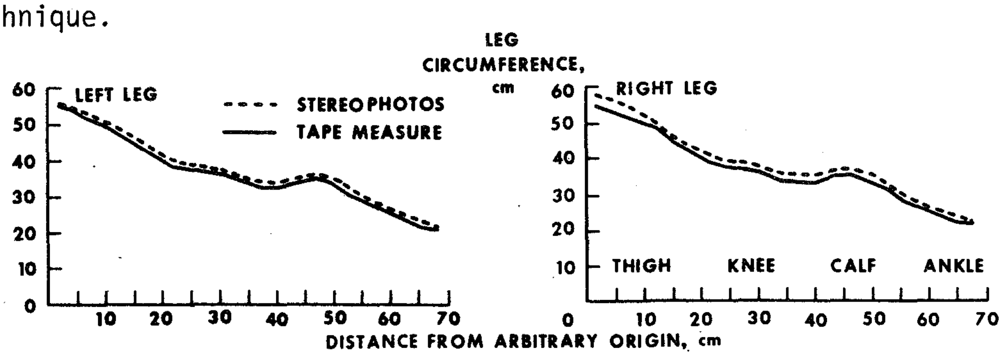

Figure 2. Comparison between tape measure and stereometric circumference measurements, Commander, Skylab 4, ten days preflight.

Figure 3 is a comparison between the mean preflight weight and volume of the nine Skylab astronauts and the first postflight determination. Density for all measurements is within the range 0.98 to 1.04. This is less than the normal range of density (1.02 to 1.10) derived from hydrostatic weighing or gas displacement (Wright & Wilmore, 1974) (3), because the volume figure includes, as well as the residual lung volume, the volume of air enmeshed in the hair, and the volume of those areas which cannot be visualized by the cameras - the axillae and perineum. These additional volumes should be reasonably reproducible from one measurement to another on the same subject, except for the hair volume, which is probably the largest single source of error. The Commander and Pilot of the final (Skylab 4) crew grew beards during the course of the flight, which again will have added slightly to their measured body volumes. It is unrealistic to calculate the density of the tissue lost during the course of the flight, as small errors in the volume determination would lead to impossible values for tissue density. Two of the crewmen - the Commander and Pilot on Skylab 4 - showed little or no weight change, although a redistribution of body volume did occur. Generally speaking, the changes in weight and total body volume were of similar magnitude, and the apparent changes in density are probably not significant.

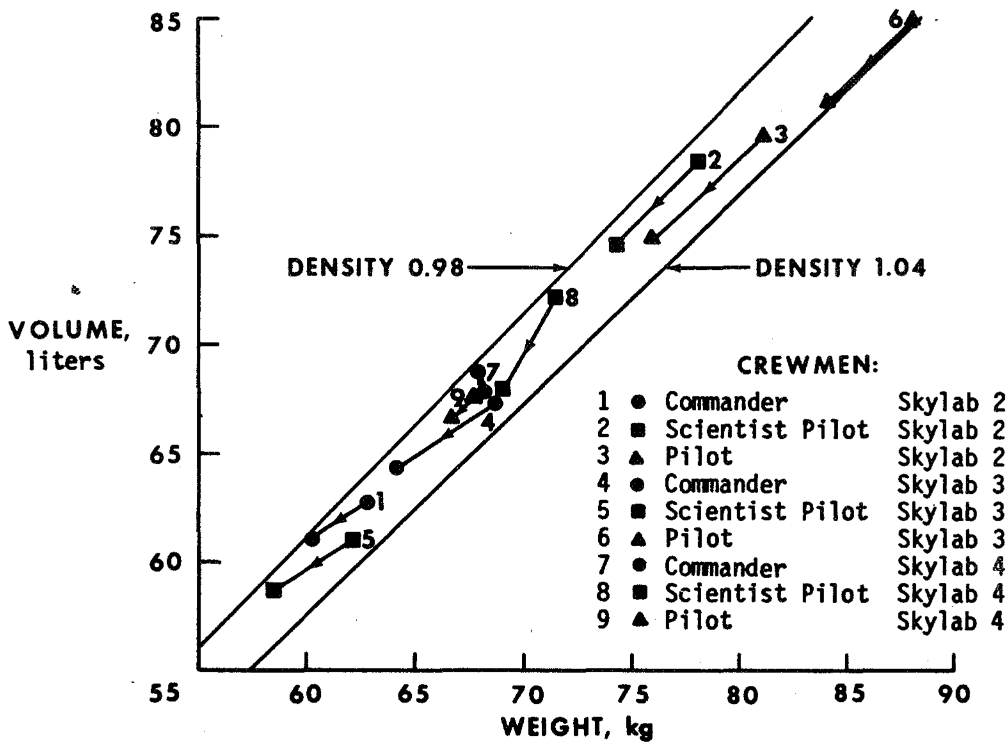

Figure 3. Comparison between mean preflight and first postflight body weight and volume.

Table I gives differences between the mean preflight and first postflight measurements of regional and total body volume, and body weight. It is difficult to reproduce the "cutoff" plane between the arms and the trunk, so that the arm volumes are subjected to considerable random variation, as is evidenced by the high standard deviation. There is no statistically significant difference in mean arm volume between preflight and postflight measurements. The mean losses of volume of 1.2 liters in the head and trunk, and 1.3 liters in the legs, are significantly different from zero ($P<0.005$). The mean preflight volume of the head and trunk is 45.8 liters, and that of the legs 18.9 liters, so that the postflight change in volume is proportionately much greater in the legs.

The head and trunk segment of the body contains the extensively fatty areas of the buttocks and abdomen. It is probable that the volume changes seen in this body segment are due more to changes in fat than to changes in muscle, whereas the legs contain much more muscle than fat, except in the grossly obese, and are more sensitive to changes in muscle bulk. Both regions of the body would be affected by changes in body fluid.

TABLE I. DIFFERENCES BETWEEN MEAN PREFLIGHT AND FIRST POSTFLIGHT DETERMINATIONS OF REGIONAL AND TOTAL BODY VOLUME, AND BODY WEIGHT

SKYLAB MISSION	CREWMAN	VOLUME (Liters) ARMS	HEAD & TRUNK	LEGS	TOTAL BODY	WEIGHT (Kg)
2 (R+0)	Commander	-0.03	-0.63	-1.00	-1.66	-2.56
	Scientist Pilot	-0.54	-1.51	-1.80	-3.84	-3.81
	Pilot	-0.86	-1.71	-2.25	-4.81	-5.17
3 (R+1)	Commander	-0.10	-2.13	-0.81	-3.03	-4.50
	Scientist Pilot	+0.20	-1.58	-0.94	-2.32	-3.66
	Pilot	-0.59	-1.82	-1.42	-3.83	-3.93
4 (R+0)	Commander	+0.22	+1.50	-0.84	+0.87	-0.18
	Scientist Pilot	-0.33	-2.52	-1.50	-4.36	-2.49
	Pilot	+0.36	-0.33	-1.03	-1.00	-0.94
MEAN		-0.19	-1.19	-1.29	-2.66	-3.03
S.D.		0.42	1.22	0.49	1.83	1.64

Figure 4 is a typical plot of the cross sectional area of the body measured against distance from the floor. The area beneath the curve represents volume. The differences between preflight and postflight measurements in the regions of the head, shoulder, and arms are slight, and result from differences in posture. Marked loss of volume is seen

in the abdomen, buttocks, and calves, and a less striking loss in the thighs. The abdominal area shows a flattening of the abdomen, and the gluteal region a reduction in volume of the buttocks, both probably resulting predominantly from loss of fat. Loss of volume from the buttocks was not observed in the Commander and Pilot on Skylab 4, who lost very little weight in the course of the flight; all crewmen lost volume from the abdomen, although the loss from this area was much greater in those who showed significant weight loss. The striking reduction in leg volume immediately postflight was investigated in more detail on the final (Skylab 4) mission, in an attempt to elucidate how much of it resulted from partial muscle atrophy, due to relative disuse of the legs in the weightless environment, and how much represented a purely temporary dehydration. The absolute loss of volume from the thigh and calf was of similar magnitude, although the much smaller dimensions of the calf resulted in a much greater proportional loss and a greater change in cross sectional area, as illustrated in figure 5.

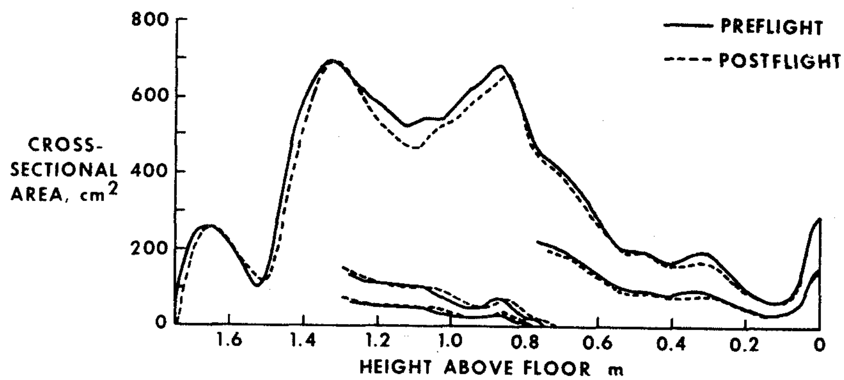

Figure 4. Preflight and postflight volume distribution, Scientist Pilot, Skylab 3.

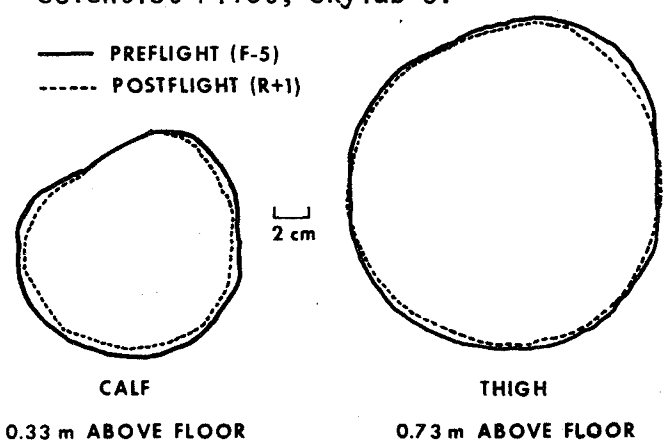

Figure 5. Comparison between preflight and postflight cross-sections of right calf and thigh, Pilot, Skylab 3.

Table II gives the differences between the volume of thigh and calf postflight in the Skylab 4 crewmen and the mean preflight value. On recovery day there was a deficit in the lower limbs of nearly 1000 milliliters, which had reduced by about a third by the following day, and had diminished to around 300 milliliters three days later. Both calf and thigh volume had returned to preflight values by the measurement made 30 days following recovery. It is clear that at least part of the deficient volume must represent missing fluid, which is replaced within a day or two of recovery, but there is probably also a reduction in bulk of the tissues of the leg. If, as seems probable, this loss of tissue represents partial atrophy of the leg muscles due to relative disuse in zero gravity, it would probably be restored fairly rapidly on return to Earth, so that the 300 milliliters deficit measured on day 4 postflight may be an underestimate of the total leg muscle lost during the flight.

TABLE II. DIFFERENCES BETWEEN MEAN PREFLIGHT AND FIRST THREE POSTFLIGHT DETERMINATIONS OF LOWER LIMB VOLUMES (SKYLAB 4)

Thigh (Both Legs)
(Liters)

	R+0	R+1	R+4
Commander	-0.37	-0.35	-0.14
Scientist Pilot	-0.69	-0.40	-0.14
Pilot	-0.34	-0.35	-0.09
Mean	-0.47	-0.37	-0.12

Calf (Both Legs)
(Liters)

	R+0	R+1	R+4
Commander	-0.41	-0.12	-0.17
Scientist Pilot	-0.58	-0.47	-0.22
Pilot	-0.46	-0.34	-0.13
Mean	-0.48	-0.31	-0.17

The mean loss of leg volume on recovery day was 1.68 liters for the Skylab 2 crew, and 1.12 liters for the Skylab 4 crew. The mean loss on day 1 postflight was 1.06 liters for the Skylab 3 crew, and 0.77 liters for the Skylab 4 crew. While it is not possible directly to compare the Skylab 2 and Skylab 3 crews, there does appear to be a

decrease in the loss of leg volume on succeeding missions. On the basis of these measurements, it seems likely that in-flight exercise, which was increased on successive flights, may have acted in opposition to the postflight loss of leg volume. How much of this opposition is mediated by the prevention of muscular atrophy, and how much by an effect on the cardiovascular system, and hence on body fluids, it is not possible to say.

CONCLUSIONS

Biostereometric analysis of body form on the nine Skylab astronauts, preflight and postflight, reveals a loss of volume of one to one and one-half liters from the legs, much of which is replaced during the first four days postflight. It is estimated that about one third of this loss represents partial atrophy of the leg muscles due to relative disuse in zero gravity, the remainder being due to a deficit in body fluid. Reduction in volume of the abdomen has been noted also, and this probably represents a small loss of body fluid, combined with a loss of body fat in all but two of the crewmen. Difficulties in distinguishing between the upper arm and the shoulder region have prevented any useful conclusions being drawn from the measurement of arm volume.

Detailed analysis of the coordinate data on body form is only partially complete, and much more detailed conclusions may be possible in the future. In contradistinction to any other form of anthropometry, the stereoscopic photographs of the Skylab astronauts are a permanent detailed record of body form, which may be reexamined at some future date to answer new questions, or to take advantage of the increased accuracy resulting from advances in technique.

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